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ARCHITECTING NETWORKED ENGINEERING SYSTEMS

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I would like to dedicate my dissertation to my daughters, Anastasija and Iva, who are my never ending motivation, and to my loving husband, Nawaz Syed, who is with me every step of the way.

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# Glossary

***Cloud Computing.*** Virtualization of software and hardware resources allowing for networked resources to be accessed as a service in a ubiquitous was and on the bases of pay-as-you-go pricing.

***Cloud-Based Design and Manufacturing (CBDM).*** A cyber-physical integration and control of manufacturing machines with CAD, CAE, ERP, and MES systems across one enterprise as a vertical integration. CBDM is a precursor for extending IoT and IoS.

***Computational Complexity.*** Mathematical model characterized by continuous and discrete-time variables, Boolean and integer variables, linear and nonlinear constraints and goals, and bounds on the variables.

***Decentralized Decisions.*** The ability of cyber physical systems to make decisions on their own and to perform their tasks as autonomously as possible. Only in the case of exceptions, interferences, or conflicting goals, are tasks delegated to a higher level.

***Decision-Based Design (DBD).*** Based on fundamental principles of decision theory and decision analysis in engineering design, integrates producer and consumer preferences into engineering design.

***Digital Platform.*** Provides decision support for engineers/designers, collaboration between different users from different domains and trains them how to understand the impacts of design decision in order to speed up the design process and facilitate the creation of quality cost-effective designs.

***Digital Thread.*** Access information from operations and enabled informed design at larger systems scale including manufacturing operations for early stage decision making the design process or making appropriate changes at operations stage.

***Digital Twin.*** Refer to computerized companions of physical assets that can be used for various purposes. Digital twins use data from sensors installed on physical objects to represent their near real-time status, working condition or position.

***High Complexity.*** Associated with a design of the system of higher order (systems that consist of many operational stations), and computational complexity (the number of design variables that are used to represent MMPs and computational models characteristics).

***Industry 4.0.*** Defined as digitized manufacturing.

***Industry 4.0 Design Principles.*** Interoperability, information transparency, technical assistance, and decentralized decisions.

***Information Transparency.*** The ability of information systems to create a virtual copy of the physical world by enriching digital plant models with sensor data. This requires the aggregation of raw sensor data to higher-value context information.

***Internet of Things (IoT).*** Is the network of physical devices, vehicles, home appliances, and other items embedded with electronics, software, sensors, actuators, and connectivity which enables these things to connect and exchange data, creating opportunities for more direct integration of the physical world into computer-based systems, resulting in efficiency improvements, economic benefits, and reduced human exertions.

***Internet of Services (IoS).*** Better known as Cloud Computing is an information technology (IT) paradigm that enables ubiquitous access to shared pools of configurable system resources and higher-level services that can be rapidly provisioned with minimal management effort, often over the Internet.

***Interoperability.*** The ability of machines, devices, sensors, and people to connect and communicate with each other via the Internet of Things (IoT) or the Internet of People (IoP).

***Novel Architecture.*** The novel design methodology.

***Operable System.*** Functional system undergoing dynamic changes.

***Original Design.*** A new design where there is no prior knowledge about the process and we need to locate the input ranges in order to achieve desired output that will satisfy certain market needs, customer preferences.

***Operable System.*** Functional system undergoing dynamic changes.

***Sensor Distribution Scheme.*** Distribution of sensors through the process.

***Smart Manufacturing.*** Strives to organize digital and physical processes across smart factories and the entire product value chain.

***Technical Assistance.*** First, the ability of assistance systems to support humans by aggregating and visualizing information comprehensibly for making informed decisions and solving urgent problems on short notice. Second, the ability of cyber physical systems to physically support humans by conducting a range of tasks that are unpleasant, too exhausting, or unsafe for their human co-workers.

***Uncertainty.*** Associated with uncertainty in the actual process or computational models used to simulate the process. Based on the source of uncertainty there is different types: (1) natural, (2) model parameter, (3) model structure, and (4) propagated uncertainty.

***Variant Design.*** There is existing knowledge about the process and different combination of variants (structures) enables engineers to design a process that will satisfy diverse market needs, customer preferences.

# Nomenclature

| | | |
|---|---|---|
| $X_i$ | : part accumulated variation up to Station *i* including Station *i*, | $[mm]$ |
| $X_{i-1}$ | : part accumulated variation up to Station *i-1* including Station *i-1*, | $[mm]$ |
| $U_i$ | : control vector at Station *i*, which is defined as the fixture error vector for both subassembly parts at Station *i*, | [mm] |
| $Y_i$ | : measurement obtained at Station *i*, | $[mm]$ |
| $V_i$ | : noise due to unmolded effects, independent from other noise, | $[mm]$ |
| $W_i$ | : sensor noise, independent from other noise, | $[mm]$ |
| $A_{i-1}$ | : dynamic matrix, characterizes variation change due to part transfer from Station *i* to / and Station *i+1*, depends on the change of locating schemes in a production stream, | $[mm]$ |
| $B_i$ | : input matrix, determines how fixture variation affects part variation at Station *i*, based on the geometry of a fixture locating layout, | $[mm]$ |
| $C_i$ | : sensor locations information at Station *i*. | $[mm]$ |
| $I$ | : unit matrix with the dimension 3n x 3n, | $[-]$ |
| $\Theta$ | : zero matrix with the dimension 3n x 3n. | $[-]$ |
| $m_r$ | : total number of measurement points on Part *r*, | $[mm]$ |
| $R_{j,r}$ | : deviations of measurement points on Part *r* at Station *i* (j=1,2,…, $m_r$), | $[mm]$ |
| $F_{i-1}$ | : feed flow rate | $[\mathrm{ft}^3\mathrm{h}^{-1}]$ |
| $F_i$ | : flow rate | $[\mathrm{ft}^3\mathrm{h}^{-1}]$ |
| $V_i$ | : volume | $[\mathrm{ft}^3]$ |
| t | : time | $[s]$ |
| $C_{Ai}$ | : concertation of A | $[\mathrm{lbmol\ ft}^{-3}]$ |
| $C_{Ai-1}$ | : feed concertation of A | $[\mathrm{lbmol\ ft}^{-3}]$ |
| $k_i$ | : reaction rate constant | $[\mathrm{h}^{-1}]$ |
| $\rho$ | : density of A | $[\mathrm{lb\ ft}^{-3}]$ |
| $c_p$ | : heat capacity of A | $[\mathrm{Btu\ ft}^{-3}\ {}^\circ F^{-1}]$ |
| $T_i$ | : reactor temperature | $[\ {}^\circ F]$ |
| $T_{i-1}$ | : feed temperature | $[\ {}^\circ F]$ |
| $\Delta H$ | : heat of reaction | $[\mathrm{Btu\ lbmol}^{-1}]$ |
| $U$ | : overall heat-transfer coefficient | $[\mathrm{Btu\ h}^{-1}\ \mathrm{ft}^{-2}\ {}^\circ F^{-1}]$ |
| $T_{Ci}$ | : jacket temperature | $[\ {}^\circ F]$ |
| $T_{C0}$ | : coolant feed temperature | $[\ {}^\circ F]$ |
| $A_i$ | : heat-transfer area | $[\mathrm{ft}^2]$ |
| $\rho_C$ | : density of coolant | $[\mathrm{lb\ ft}^{-3}]$ |
| $c_{pC}$ | : heat capacity of coolant | $[\mathrm{Btu\ ft}^{-3}]$ |

| | | |
|---|---|---|
| $V_{Ci}$ | : volume of the jacket | $[ft^3]$ |
| $F_{Ci}$ | : coolant flow rate | $[ft^3 h^{-1}]$ |
| $E$ | : activation energy | $[Btu\ lbmol^{-1}]$ |
| $R$ | : reference or nominal value | $[-]$ |
| $A_{si}$ | : side heat-transfer area | $[ft^2]$ |
| $A_{bi}$ | : bottom heat-transfer area | $[ft^2]$ |
| $A_{si}^{R}$ | : reference side heat-transfer area | $[ft^2]$ |
| $V_i^R$ | : reference volume | $[ft^3]$ |
| $x_{1i}$ | : normalized reactor holdup | $[-]$ |
| $x_{2i}$ | : concentration of reactor A | $[-]$ |
| $x_{3i}$ | : reactor temperature | $[-]$ |
| $x_{4i}$ | : coolant temperature | $[-]$ |
| $x_{4i}$ | : coolant temperature | $[-]$ |
| $q_i$ | : normalized flow rate | $[-]$ |
| $q_{Ci}$ | : normalized coolant flow rate | $[-]$ |
| $\alpha_i$ | : ratio of coolant flow rate and flow rate and | |
| $\tau$ | : | $[-]$ |
| $\phi_i$ | : | $[-]$ |
| $\Upsilon$ | : | $[-]$ |
| $\mu_i$ | : ratio of flow rate and coolant flow rate | $[-]$ |
| $\upsilon_i$ | : | $[-]$ |
| $\beta$ | : | $[-]$ |
| $\xi$ | : | $[-]$ |
| $\delta_{si}$ | : thickness of side heat-transfer area | $[-]$ |
| $\delta_{bi}$ | : thickness of bottom heat-transfer area | $[-]$ |
| $f(x_{3i})$ | : | $[-]$ |
| $k_0$ | : Arrhenius constant | $[-]$ |
| $\Delta H$ | : heat of reaction | $[Btu\ lbmol^{-1}]$ |
| $ODF$=1 | : overdesign factor in the reactor volume obtain DIS | $[-]$ |
| $T_i$ | : strong constraint | [°F] |
| $F_{Ci}$ | : assumption | $[ft^3 h^{-1}]$ |
| $k$ | : reactor rate constant at reactor temperature | $[-]$ |
| $Q_{max}/Q$ | : controllability index of Luyben | $[-]$ |
| $\Delta T$ | : temperature difference between jacket and reactor | [°F] |
| $\lambda_{ij}$ | : $j^{th}$ eigenvalue of $i^{th}$ reactor (i is omitted for single reactors) | $[h^{-1}]$ |
| i | : reactor number | $[-]$ |

# Abstract

The primary goal in this dissertation is to create a new knowledge, make a transformative influence in the design of networked engineering systems adaptable to ambitious market demands, and to accommodate the Industry 4.0 design principles based on the philosophy that design is fundamentally a decision making process. The principal motivation in this dissertation is to establish a computational framework that is suitable for the design of low-cost and high-quality networked engineering systems adaptable to ambitious market demands in the context of Industry 4.0.

Dynamic and ambitious global market demands make it necessary for competitive enterprises to have low-cost manufacturing processes and high-quality products. Smart manufacturing is increasingly being adopted by companies to respond to changes in the market. These smart manufacturing systems must be adaptable to dynamic changes and respond to unexpected disturbances, and uncertainty. Accordingly, a decision-based design computational framework, Design for Dynamic Management (DFDM), is proposed as a support to flexible, operable and rapidly configurable manufacturing processes. DFDM has three critical components: adaptable and concurrent design, operability analysis and reconfiguration strategies. Adaptable and concurrent design methods offer flexibility in selection of design parameters and the concurrent design of the mechanical and control systems. Operability analysis is used to determine the functionality of the system undergoing dynamic change. Reconfiguration strategies allow multiple configurations of elements in the system.

It is expected that proposed computational framework results in next generation of networked engineering systems, where tools and sensors communicate with each other

via the Internet of Things (IoT), sensors data would be used to create enriched digital system models, adaptable to fast-changing market requirements, which can produce higher quality products over a longer lifetime and at a lower cost. The computational framework and models proposed in this dissertation are applicable in system design, and/or product-service system design. This dissertation is a fundamental research and a way forward is DFDM transition to the industry through decision-based design platform. Decision-based design platform is a step toward new frontiers, Cyber-Physical-Social System Design, Manufacturing, and Services, contributing to further digitization.

# CHAPTER 1

# DECISION-BASED DESIGN OF NETWORKED ENGINEERING SYSTEMS

The principal goal in this dissertation is to create a new knowledge, make a transformative influence in the design of networked engineering systems adaptable to ambitious market demands, and accommodate the Industry 4.0 design principles based on the philosophy that design is fundamentally a decision making process. The principal motivation is to establish a computational framework suitable for the design of low-cost and high-quality networked engineering systems adaptable to ambitious market demands. Further, in this dissertation the foundation is created for a way forward by framing the problem, identifying the research gaps and questions worthy of investigation.

In this chapter, a foundation of the dissertation is presented. The motivation presented in Section 1.1, where two topics are discussed (1) how a change of demands changed the industry and how manufacturing processes evolved, and (2) frontiers in Industry 4.0 and how challenges in smart manufacturing systems are addressed through design. Further, the idea of the computational framework, Design for Dynamic Management, is introduced. The background presented in Section 1.2, is anchored in concurrent design, concept exploration, and decision-making at the early stages of design. The frame of reference presented in Section 1.3, where (1) Stream of Variation (SoV) modeling, (2) the compromise Decision Support Problem (cDSP) construct, (3) solution space exploration, (4) verification and validation, and (5) robust design is considered. The principal goal of the dissertation is summarized in Section 1.4. Further, the contributions are justified by summarizing deliverables and research gaps are identified that will be further addressed as a way forward. The overview and validation strategy of the dissertation is presented in Section 1.5.

## 1.1 Motivation - Design of Networked Engineering Systems in the Context of Industry 4.0

Social progress, as well as energy sustainability (Cagan and Vogel, 2002) and scientific discovery (Pendergast and Schauwecker, 1998; Bronowicki, et al., 2003; Bronowicki, 2006; Ma, et al., 2012), depends on technology development which is related to breakthrough innovations in engineering design (Chen, et al., 1997) which is difficult to achieve. In some cases the adjustment to existing systems is not an alternative and novel architectures (Chakrabarti, et al., 2011) is the only option, especially in the early stages of design. However, it is challenging to consider novel architectures due to increased complexity, possible increased design time (Chen, et al., 1997), difficulty to predict performance, and need for different computational frameworks. Advancements in architecture integration, solution space exploration, and rigorous quantitative evaluation (Cagan, et al., 2005) are necessary in order to overcome these challenges. The primary goal in this dissertation is to create a computational framework for architecting networked engineering systems (NES) by accounting for adaptability, operability, and reconfigurability in design where in the early stages of design designers do not yet have design intuition nor insights in the system, product-service system capabilities. The computational framework proposed in this dissertation includes adaptable concurrent design, system operability analysis, and system reconfiguration strategy, supported by the effective decision-making network, extensive solution space exploration, and managing uncertainty.

In Section 1.1.1, it is discussed how different demands changed industry over time, the trend of the fourth industrial revolution, and how with industrial revolution manufacturing processes evolved. Design of smart manufacturing systems, challenges and what is required to overcome these challenges is presented in Section 1.1.2.

### 1.1.1 Production Engineering in Industry 4.0

The first industrial revolution took place from the 18$^{th}$ to 19$^{th}$ centuries in Europe and America, where the use of water and steam power lead to mechanize production, first column first row in Figure 1.1. The second industrial revolution took place between 1870 and 1914, where the use of electric power leads to mass production, second column first row in Figure 1.1. The third industrial revolution started during the 1980s and is ongoing, where the use of electronics and information technology lead to automate production, third column first row in Figure 1.1. Now we are entering in the fourth industrial revolution that is building on the third, as a result of the digital revolution that has been occurring since the middle of the last century, fourth column first row in Figure 1.1. The fourth industrial revolution is characterized by a fusion of technologies that is blurring the lines between the physical, digital, and biological spheres (Schwab, K., 2015).

*The Fourth Industrial Revolution*

Industry 4.0 (Made in China 2025) refers to technological evolution from embedded systems to cyber-physical systems or simply put, the fourth industrial revolution of the Internet of Things (IoT), Data, and Services according to MacDougall (MacDougall, 2014). Further, with industrial production machinery tasks are no longer simply performed and product produced, but rather the product itself communicates with production machinery and tell it exactly what to do as explained by MacDougall

(MacDougall, 2014). As explained in German Trade and Invest (GTAI) article "INDUSTRIE 4.0 connects embedded system production technologies and smart production processes to pave the way to a new technological age which will radically transform industry and production value chain and business models".

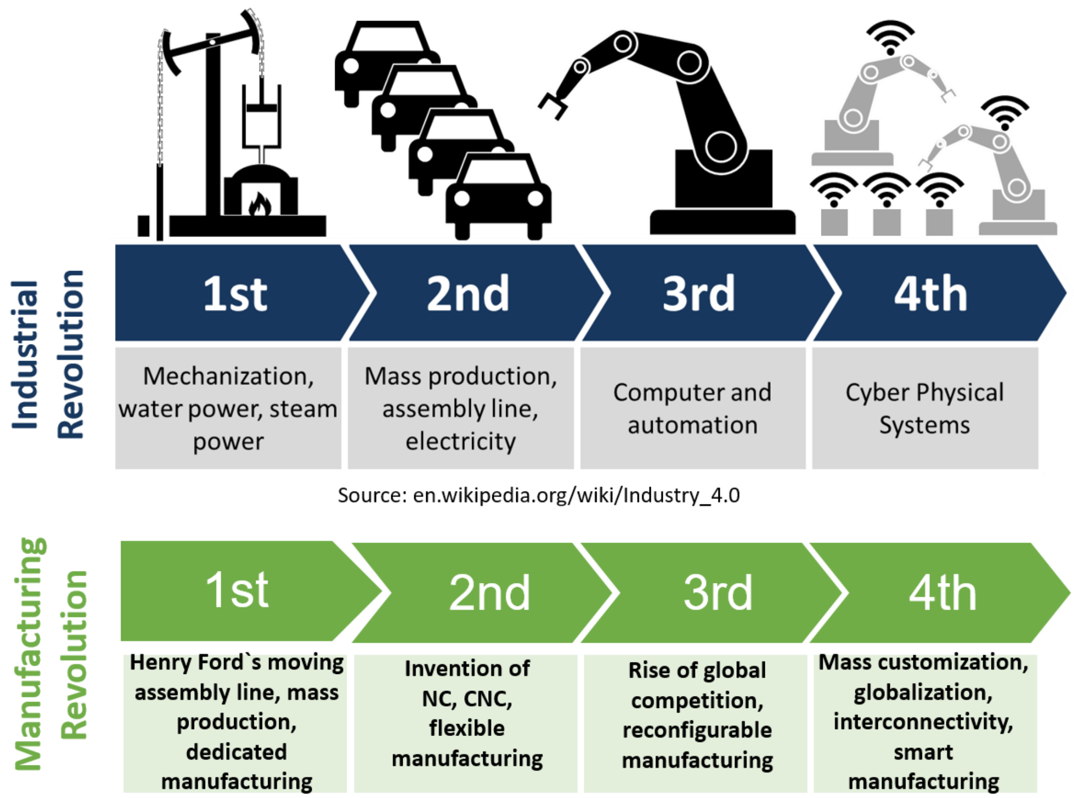


**Figure 1.1. Evolution of Manufacturing Processes with Industrial Revolution**

*Cyber-Physical Systems*

Use of Cyber-Physical Systems (CPS) joins the virtual and physical worlds in order to create one networked world where objects communicate and interact with each other, MacDougall (MacDougall, 2014). CPS is the evolution of the third industrial revolution, from existing embedded systems. CPS is the foundation of an Internet of Things (IoT), which combines with the Internet of Services (IoS) to achieve Industry 4.0 according to MacDougall (MacDougall, 2014). IoT and IoS are "enabling technologies" sets the boundaries between the virtual and the real worlds and make multiple innovative applications, Figure 1.2, MacDougall (MacDougall, 2014). CPS also, represents a break from existing market and business models, as revolutionize new applications, service providers, and value chains, MacDougall (MacDougall, 2014).

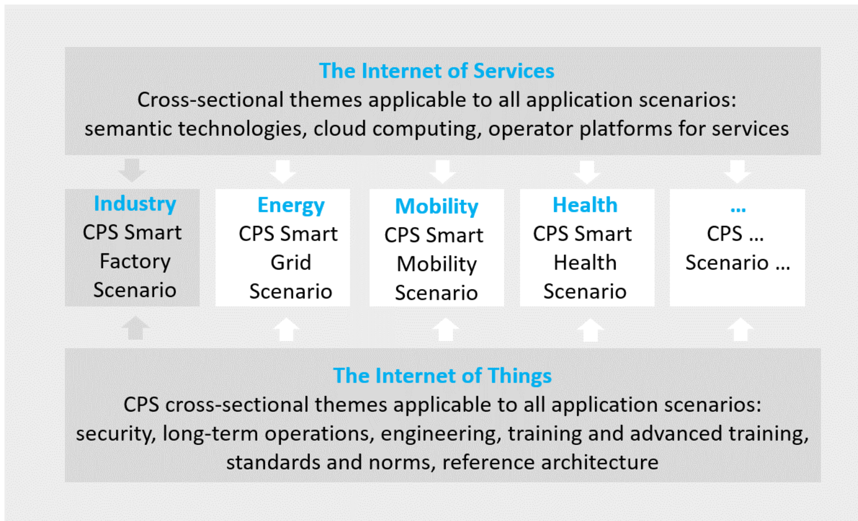


**Figure 1.2. Information and Communications Technology (ICT) as Innovation Motor for All Fields of Demands – Relevance of the Internet of the Future (MacDougall, 2014)**

Globalization, urbanization, demographic change and energy transformation are the driving forces of change. In the future, CPS will have the main role in overcoming the fundamental challenges posed by a scarcity of natural resources, energy change, sustainability, and demographic change MacDougall (MacDougall, 2014).

*The Fourth Manufacturing Revolution*

With industrial revolutions manufacturing processes evolved, the second row in Figure 1.1. The first manufacturing revolution started when Henry Ford's invent moving assembly line in 1913 which was the beginning of the mass production paradigm, first column second row in Figure 1.1. Dedicated manufacturing processes introduced the Manufacturing Revolution 1 (Koren, and Shpitalni, 2010). Dedicated manufacturing has high productivity rate for the single part type production, and was popular until the mid-

90s. The second manufacturing revolution started with the invention of NC, and later CNC in the 1970s that facilitated flexible manufacturing systems (FMS) in early 80s (Koren, and Shpitalni, 2010), second column second row in Figure 1.1. Flexible manufacturing has high flexibility and quality for multiple part type production. However, as market increased followed by unexpected changes in demand resulting from global competition in mid-90s reconfigurable manufacturing system (RMS) was introduced (Koren, and Shpitalni, 2010) which lead to the Manufacturing Revolution 3, third column second row in Figure 1.1. Reconfigurable manufacturing is adaptable to rapid structural changes.

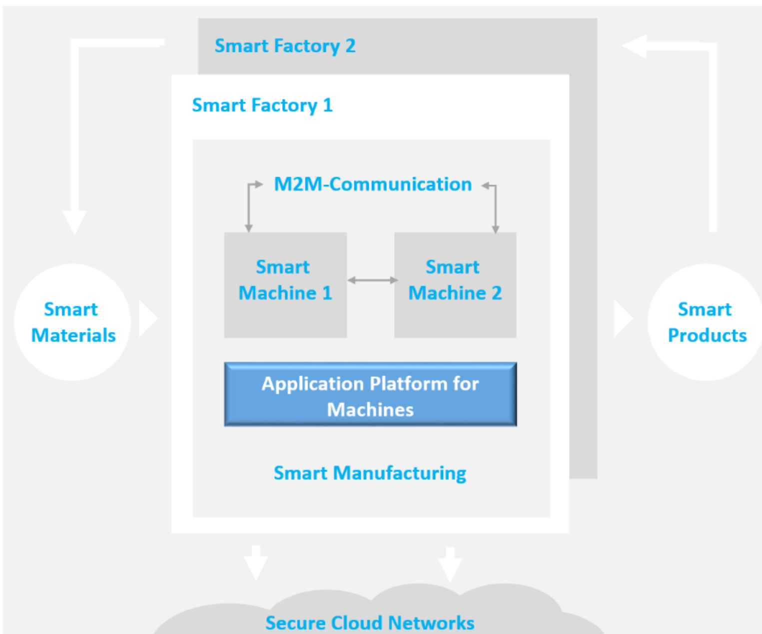


**Figure 1.3. Industry 4.0 Smart Manufacturing Pipeline (CPS Secure Networks)**

The merging of the virtual and the physical worlds through CPS, a fusion of technology and business processes are bringing us to the age of the fourth industrial revolution and the concept of “smart factory” and within “smart manufacturing”. Smart factory (SF) products, resources, and processes are characterized by CPS, Figure 1.3, (MacDougall, 2014). In comparison with classic production system SF provides real-time quality, time, resource, and cost-efficiency. Smart manufacturing (SM) enables flexible production, big data analysis in real-time, and connectivity among elements in a system. SF and SM insist on adaptability, flexibility, reconfigurability, operability, fault tolerance and risk management, self-adaptability and learning characteristics.

SF presents a production revolution regarding cost and time savings, innovation, and the “bottom-up” production creation model where networking capacity creates new and more market opportunities (MacDougall, 2014). In comparison with conventional manufacturing SM enables:

- CPS-based production processes where determining and identifying operational activities at any given moment, configuration options and production conditions, and communications among other units;
- Individualize customer product manufacturing; and
- Resource and energy-efficient production.

### 1.1.2 Design of Smart Manufacturing Systems in the Context of Industry 4.0

Dynamic changes in the market due to wide variations in customer needs lead to mass customization where enterprises have to be capable to adjust the manufacturing processes according to the wide variations of product design and substantial change of product scale. On the other hand, global competition requires enterprises not only to provide the cost-effective manufacturing processes but also to improve the quality of product and shorten time to market. Smart manufacturing is increasingly being adopted by companies to respond to these changes in the market. It is required to obtain flexible production, big data analysis in real time, and establish/maintain connectivity among elements in the system. These smart manufacturing systems must be adaptable to dynamic changes and respond to unexpected disturbances, and uncertainty.

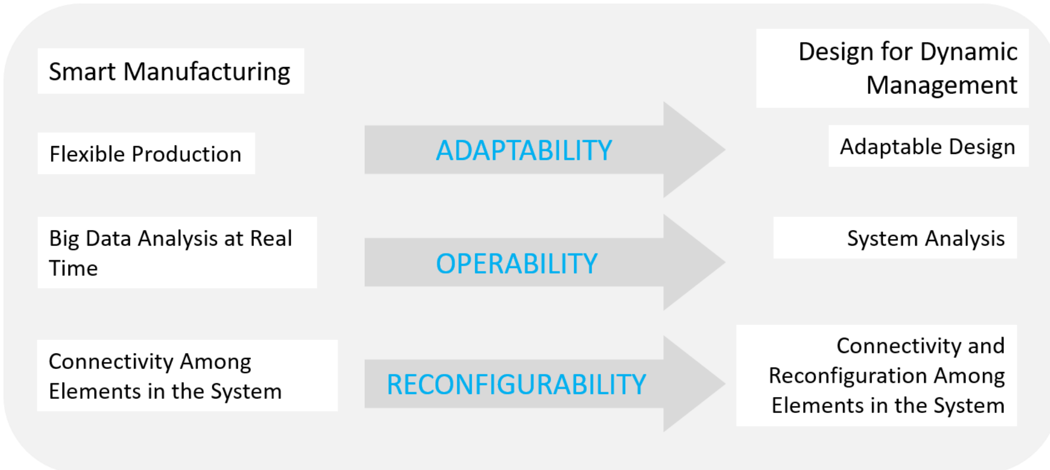


**Figure 1.4. Big Picture – Design for Dynamic Management as Support to Smart Manufacturing**

In order to the maintain the low-cost process and high quality of a product, there needs to design a system to be adaptable to dynamic and ambitious market demands in a trend of globalization. Hence, a need for a new computational framework a decision-based design computational framework, Design for Dynamic Management, Figure 1.4, and achieving the following features (1) flexible production through adaptable design; (2) system analysis through operability analysis; and (3) ensuring connectivity among elements in the system by allowing multiple reconfigurations within the system through system reconfigurability.

The background and the frame of reference of decision-based design computational framework, Design for Dynamic Management, for the design of networked engineering systems are presented in Sections 1.2 and 1.3. A decision-based design computational framework is anchored in the concurrent design of both mechanical and control system, Section 1.2.1, concept exploration (determining top-level design specifications), Section 1.2.2, and design is decision-making process, Section 1.2.3.

## 1.2 Background - Design of Networked Engineering Systems

Most new designs are connected with innovation as adaptations of the existing system (Bers, et al., 2009; Wagner, 1993; Pahl and Beltz, 2013) and rarely connected with inventions. The reason is designers tend to guide their solution toward existing one, and limit its own creativity by a fixation on particular design (Carryer, et al., 2011; Condoor and LaVoie, 2007; Linsey, et al., 2010). Creating new architecture is highly challenging followed by aversion from designers (Ottino, 2004) and engineering organizations (Collopy and Hollingsworth, 2011; Ross, et al., 2005; Weigel and Hastings, 2004). Furthermore, innovation greatest enemy is an aversion toward challenges (Assink, 2006). Novelty in system design has a potential for performance breakthroughs followed by increased complexity in product development, uncertainties, cost, and time to market (Bers, et al., 2009; Veryzer, 1998; Tatikonda and Rosenthal, 2000; Buede, 2016). Architecture is often designed to overcome forward mentioned challenges (Bers, et al., 2009). Traditional design processes (Veryzer, 1998; Benner and Tushman, 2003; Vajna, et al., 2005) are not conducive to a successful realization of unconventional design. Moreover, a designer tends to adopt new solutions for system design only when they are out of options (Steltzner, et al., 2006). It can be concluded that new design processes are needed in order to move forward breakthrough innovations (Veryzer, 1998; Benner and Tushman, 2003; Magnusson, et al., 2003; Williams, 1999; Allen, et al., 2011). New architecture exploration can help designers to escape from conventional design solutions (Chakrabarti, et al., 2011).

In this dissertation, the focus is on dynamic management of networked engineering system through concurrent engineering of both systems under different types of uncertainty through decision-based design, solution space exploration, and quantitative evaluation of new computational framework.

### 1.2.1 Concurrent Engineering of a Mechanical and a Control System

Concurrent Engineering (CE) or "simultaneously engineering" has a huge influence in the design of complex systems. CE is recognized as a viable design approach where the design of a product, related manufacturing processes, and support systems are considered simultaneously.

With the use of CE, the goal is to achieve optimization of characteristics and processes related to the product (Hutchison and Hoffman, 1990). The concept of CE is getting in the spotlight due to the increasing competitiveness in the global market for new products delivered in the shortest time. Hence, the design process of complex systems undergo significant changes and still changing.

The difference between sequential and concurrent designs approaches based on CE principles, presented in Figure 1.5., where time spent in the conceptual design phase is increased and multidisciplinary and interdisciplinary knowledge exchange is introduced (Chen, 1995). As a result, design knowledge and freedom increased producing efficient design process. Further, in the early stages of design, Figure 1.5, when a designer has limited knowledge about the process, mathematical models used to represent the process is incomplete and inaccurate optimization cannot be used because uncertainty cannot be mitigated but rather managed.

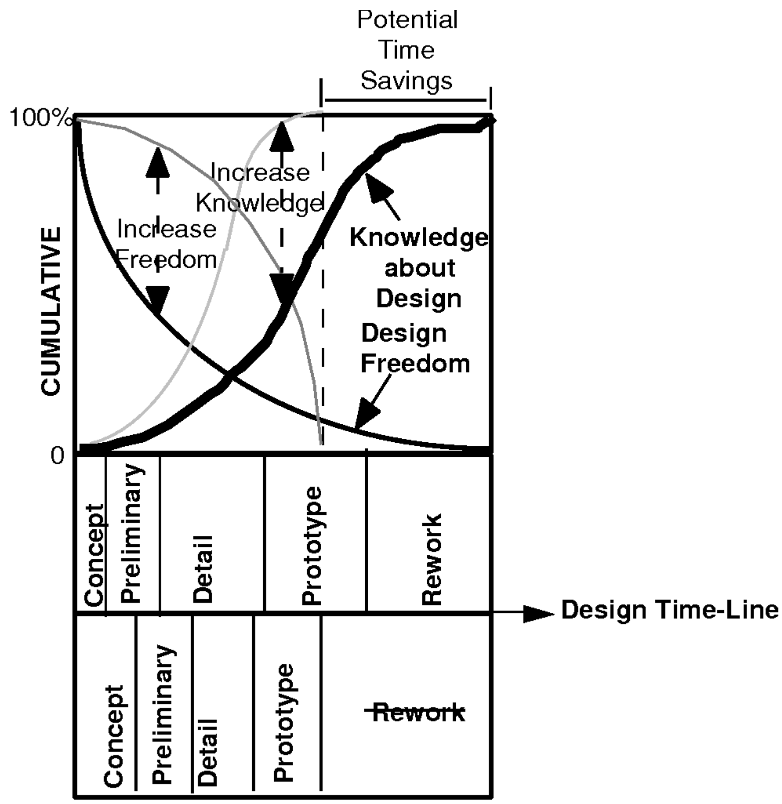


**Figure 1.5. Improve Design Productivity by Increasing Design Knowledge and Maintaining Design Freedom (Chen, et al., 1996)**

The design of NES in the early design stages expect the prediction of response of the system and performance as a function of design variables in different stages using demanding numerical simulations which requires extensive computational resources and sufficient information. However, there is a lack of information in the early stages of design. Further, since concurrent design based on CE principles is still in the phase of philosophical, not technological development cannot be implemented in many forms and comprehensive approach is needed (Chen, 1995).

Conventional design methods where mechanical system design is followed by control system design cannot fully account for diagnosable, controllable, cost-effective processes, with satisfying the dimensional quality of products. Majority of established design methods involve simplified design process which accounts for diagnosability, controllability, and cost-effectiveness separately. Further, conventional optimal control strategies (Ding, et al., 2002; Mantripragada and Whitney, 1999; Ding, et al., 2003; Izquierdo, et al., 2007) are used where model uncertainty is not included.

The proposed computational framework, Architecting Networked Engineering Systems, supports comprehensive treatment of engineering process design in order to account for process diagnosability, controllability, and cost-effectiveness under different types of uncertainty. However, high-fidelity models are still impractical to use in the early stages of design. Hence, in this dissertation, a strategy for managing the top-level design approach is considered. This dissertation involves foundational theoretical and numerical development.

So far, the focus has been on the "Big Picture" which is the design of NES, Section 1.1.2, and concurrent design of NES, Section 1.2.1. Further, in Sections 1.2.2, and 1.2.3 top-level design approach is discussed and challenges in decision making in the early stages of design. Tools related to research areas and detailed review is presented in Sections 2.1 – 2.3.

### 1.2.2 Concept Exploration - Determining Top-Level Design Specifications

Concept exploration is a process of evaluating different design approaches and is influenced by way overall design requirements (goals and constraints) are used. Overall design requirement can be used in two ways (Luger and Stubblefield, 1990) (1) a priori constraining for generating possible design structures to be consistent with them, (2) a posteriori testing where a possible design satisfy design requirements. A priori use of design requirements involves analysis and transformation of the design requirement which directly influences the generation of solutions. A posteriori use of design requirements includes analysis and evaluation of a possible solution and the degree to which possible solution satisfy these requirements (Chen, 1995). Further, there are two ways to determine top-level design specifications based on the use of design requirements (1) optimization-based approach (a priori constraining), and (2) simulation-based approach (a posteriori testing). However, an ideal concept exploration approach supports both activities a priori constraining and a posteriori testing. This concept exploration method provides a broad view of the entire design space and generates information about possible useful regions of the design space.

### 1.2.3 Design Decisions at Early Stages of Design

In the early stages of design models that represent NES are incomplete, inaccurate, without sufficient data, and when sheer size and complexity of design problem is considered attaining optimal solution is impossible. It is expected that there is the best solution to any problem. However, that is not the case and at best solutions are good enough (Simon, 1980), and satisfies the most important goals and constraints. Good enough solution goes with agenda, heuristic or assumption made by a designer based on available information at certain point of time.

In the early stages of design, Figure 1.5, there is considerable unpredictability, models used to represent the process may be incomplete and inaccurate due to the limited knowledge about the process. Hence, the robust design approach for such design, particularly when capturing the system behavior across a wide design space, is more useful than optimization.

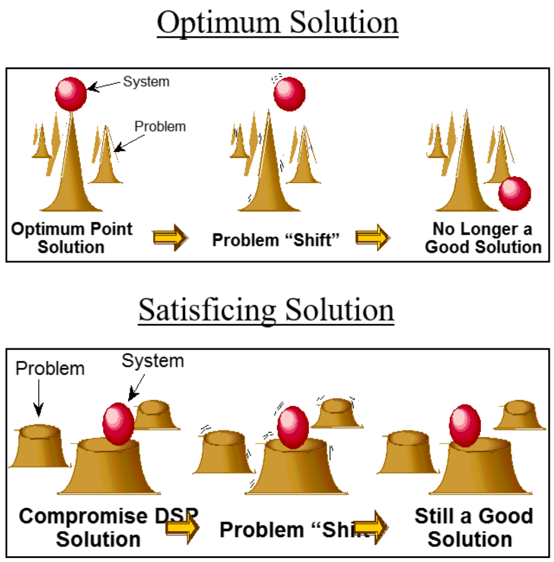


**Figure 1.6. Robust Solution with Respect to the Evolution of the Problem**

Acknowledging and managing uncertainty, solution space exploration, and identifying robust solutions is what made the influence on the author`s work in this dissertation, the design of NES in the early stages of design. Further, quality characteristics that are considered in dissertation are (1) comprehensive, incorporating knowledge from multiple disciplines, such as mechanical, industrial and control engineering; (2) robust, insensitive to variations in uncontrollable and controllable system factors that can appear in later stages of design or during operations; (3) flexible, variations are allowed within a priori prescribed range; (4) functional, achieving system functionality (operability) with change in the requirements; and (5) reconfigurability, allowing multiple reconfiguration of elements in the system.

The frame of reference in the design of networked engineering systems is presented in Section 1.3. Further, the Stream of Variation (SoV) model from Control Theory, Section 1.3.1, compromise Decision Support Problem (cDSP) construct from Decision-Based Design, Section 1.3.2, solution space exploration, Section 1.3.3, the validation square, Section 1.3.4, and accounting for uncertainty, Section 1.3.5 is what influenced the author of this dissertation.

## 1.3 Frame of Reference - Design of Networked Engineering Systems

We advocate that the design process is the decision-based activity where the principal role of designer/engineer is to make decisions. A more typical definition is the design process is an activity where a description of a system, product-service system satisfies a requirement in response to a stated goal and/or set of requirements. A design process is involved with the invention when a new product is created or with innovation where an existing system, a product-service system is improved. The outcome of the design process are multiple solutions to changing measures of quality, therefore, the fundamental duty of a designer is to make a decision (Mistree, et al., 1990). Adequate comprehension of inherent elections and uncertainty within the context of design leads to legitimate design decisions. Currently, there is a great concern regarding efficiency, equity, sustainability and profitability of a new system, and product-service system design. Hence, there is strong inspiration to develop theories and approaches in order to explore the design and aspiration spaces (Smith, et al., 2014). Particularly, the mentioned issues are also the divers that inspire the academic design community and the author of the dissertation.

Typically, design choices are explored a priori where accurate mathematical models are build and exercised in order to gain some understanding of models behaviors and emergent properties. However, such models can easily become highly complicated. Moreover, grow of knowledge in a complex system requires the management of both complication and uncertainty. In design of NES, uncertainty management raises concerns such as imprecise process, the lack of knowledge of the process, lack of knowledge in models and information propagation in a chain of models, unpredictability of a physical system, and the necessity to explore alternatives. Furthermore, there are the challenges in capturing implicit knowledge, extract knowledge from data and scenarios, and developing design methods for decision-based design.

In a model-based design of complex systems, designers have two options using the exact equations for predicting the system behavior or generating an approximation of the system behavior using heuristic methods. Usually, designer resorts to the second option because the first option is highly demanding on computational resources. Further, the method to approximate system behavior has to be both accurate and efficient according to Chen (Chen, 1995). The focus is on the approximation of the design behavior, and design space in this dissertation.

In simulation-based design, designer simulates system performance for different design concepts and assess the merits of possible designs. The advantages are providing the possibility to explore whole design space, generating and investigating new ideas, providing insight in dependency between parameters, and it is closer to the nature of the design process. Most used simulation-based design methods are (1) Grid Search used on ships Georgescu (Georgescu, et al., 1990), impractical in design of complex systems; (2) Random Generation used on ships design (Smith, 1993), extensive computational time in design of complex system; (3) Monte Carlo Simulation (Siddall, 1984), although accurate computationally expensive; and (4) Design of Experiment (DOE) Techniques (Mistree, et al., 1993).

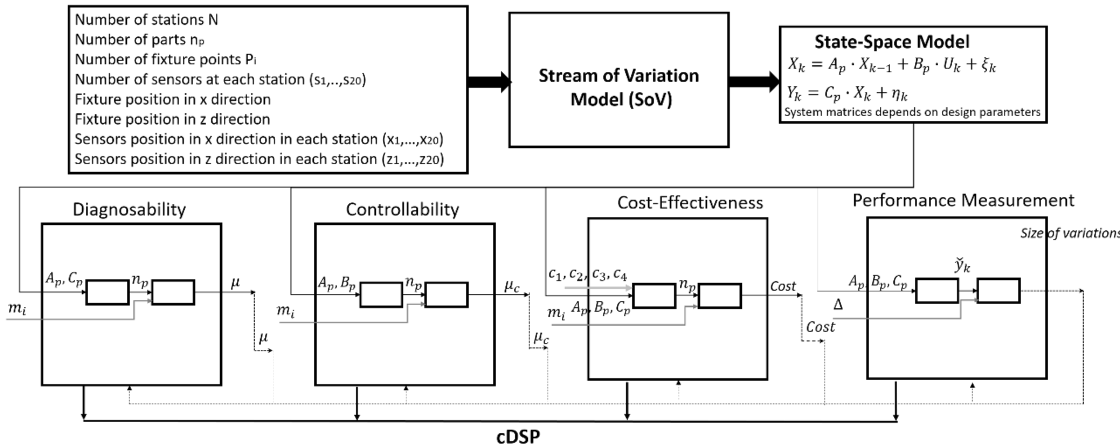


**Figure 1.7. Connection between SoV and cDSPs**

The author adopted a model-based approach in the decision-based design of NES where challenges such as acknowledging models can have different levels of fidelity, may be incomplete and possibly inaccurate in the early design stages and are considered in the dissertation. Further, the author adopted concurrent design of both mechanical and control system in design of NES, where she advocates that there is a need to establish connectivity among design parameters of the mechanical (tools on operational stations) and control systems (measuring sensors on sensing stations) through SoV, Section 1.3.1, and cDSP models, Section 1.3.2, presented in Figure 1.7.

### 1.3.1 Control Theory – Stream of Variation (SoV) Model

In NES such as multistage manufacturing processes (MMPs), products are manufactured through multiple operations or stages where the product quality is typically reflected by the variations of Key Product Characteristics (KPCs) (Zhong, 2009). During production, due to part variations and process variations, such as tool error, at each stage, the KPCs of a subassembly will deviate from a nominal position. These variations will be carried to the next stage and further interact with the assembly process. Further, these variations can be propagated to the downstream stages and accumulated into the final product. In case that the size of final accumulation is large enough, the quality of the production process will be diminished.

The propagation of variation in MMPs raises a challenge in achieving the quality of the production process. Minimizing the variation of subassembly at the current stage alone may not lead to the best final product quality. In order to achieve effective control in an MMP, three components are necessary (1) a model that captures the variation flow, i.e., the Stream of Variation model, (2) real-time sensing technologies to measure the variation, and (3) Programmable Tooling (PT) to perform control actions to suppress the variation (Zhong, 2009).

The propagation of variation in MMPs, described by the SoV modeling, by exploring the relationship of variation sources and geometric information of each operating station based on design information, especially product and process geometry (Jin and Shi, 1999). Sov modeling has then been utilized as the mathematical basis in various applications such as process modeling, design evaluation, diagnosis, tolerance synthesis, active control, and other areas (Shi, 2006).

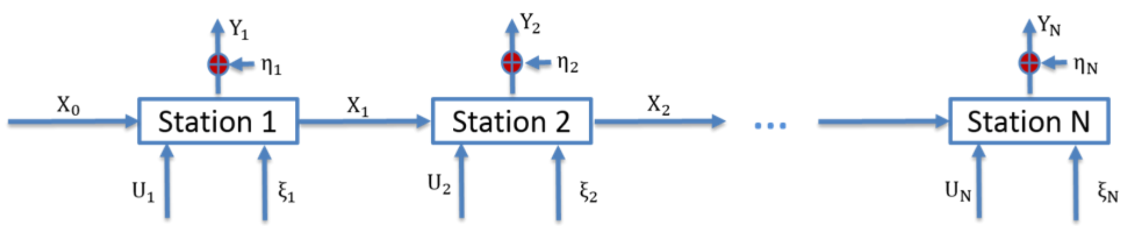


**Figure 1.8. Diagram of Multistage Assembling Process (Ding, et al., 2002)**

The SoV model, which is used to describe the impact corrections have on the final quality of the product according to Jin and Shi (Jin and Shi, 1999; Shi, 2006), is presented both graphically, Figure 1.8, and mathematically, Chapter 3, Section 3.31.

In Figure 1.8, a multistage assembling process is illustrated. Parts enter the production line from Station 1 with initial fabrication errors, $x_0$. At Station 1, the part control action $u_1$ is first applied through PT, while other unmodeled process errors, $\xi_1$, will add to the variation of the parts. The designed operation at Station 1 then takes place and the state of the subassembly changes to $x_1$. The subassembly is then transferred to the next station, and variations propagate and accumulate similarly as more parts/subassemblies are joined together, until the finished assembly exits the production line at the final Station N. The KPC is measured at the final Station N as well as intermediate stations such as Station k. The measurement $y_N$ is obtained with sensor errors $\eta_N$ (Zhong, 2009).

### 1.3.2 Decision-Based Design – compromise Decision Support Problem (cDSP)

The design is fundamentally a decision making and model-based process based on the Decision Support Problem (DSP) construct philosophy (Marston, et al., 2000; Muster, et al., 1988). Foundational to our thinking is that better design outcomes flow from a structured approach to defining and connecting associated decisions models. Further, once a model is created it can be explored to develop insights leading to greater understanding and better designing (Smith, et al., 2014). The applications of this approach include the design of aircraft, mechanisms, thermal energy systems, the design of ships, damage tolerant structural and mechanical systems, composite materials, and the concurrent design of multi-scale and multi-functional materials, and products (Mistree, et al., 1990). Key applications span inter alia specification development (Chen, et al., 1999; Lewis, et al., 1999), robust design (Allen, et al., 2006; Chen, et al., 1997; Chen, et al., 1996; Seepersad, et al., 2006), product families (Simpson, et al., 1999; Simpson, et al., 2001), the integrated design of materials and products (Choi, et al., 2008; McDowell, et al., 2009; Panchal, et al., 2007; Seepersad, et al., 2005), different mechanical systems (Chen, et al., 1994; Hernamdez and Mistree, 2000; Koch, et al., 1998; Sinha, et al., 2013), and concurrent design of a mechanical and a control system (Milisavljevic, et al., 2015). Further, in the dissertation, a flexible, functional and reconfigurable design of NES under uncertainty is adding to the forward mentioned list.

The design decision and model-based approach in the physical world are presented in Figure 1.9. In cases where the decisions relate to complex systems such as NES, dilemmas exist and actions taken have high impact, the process is iterative and certain rationale is required, Figure 1.9. It is possible to develop new perspectives through understanding emergent properties and discover new solutions in the process.

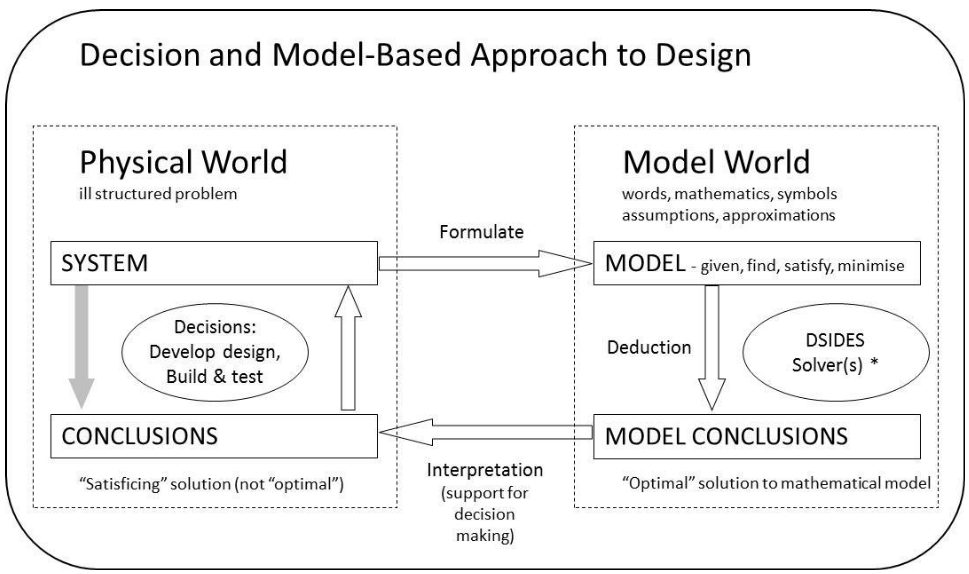


**Figure 1.9. Modelling the Physical World (Smith, et al., 2014)**

The key concept is there are two types of decisions, selection and compromise, and any complex design can be represented by mathematical modeling a network of compromise and selection decisions (Mistree, et al., 1991; Mistree, et al., 1993).

In dissertation, NES is represented through mathematical modeling a network of compromise decisions where the compromise Decision Support Problem is framed as:

---

**Given**

An alternative to be improved through modification,
Assumptions used to model the domain of interest,
The system parameters (fixed variables), and
The constraints and goals for the design;

**Find**

The independent *system variables* values (they describe the artifact's physical attributes), and
The *deviation variables* values (they indicate the extent to which the goals are achieved); which

**Satisfy**

The *system constraints* that must be satisfied for the solution to be feasible,
The *system goals* that must achieve, to the extent possible, a specified target value, and
The lower and upper *bounds* on the system variables and *bounds* on the deviation variables, in order to

**Minimize**

The *deviation function* that is a measure of the deviation of the system performance from that implied by the set of goals and their associated priority levels or relative weights.

---

The parallel between "demands" and "wishes" of Pahl and Beitz (Pahl, et al., 2007) can be drawn with the compromise DSP. The demands in the DSP are constraints and bounds. The wishes in DSP are goals (Smith, et al., 2014). Further, feasible design space is defined by the constraints and bounds. Aspiration space is defined by the goals. Further, solution space is defined by the feasible and aspiration space.

The constructs used in DSIDES are:

- Domain independent modelling framework incorporating a solution algorithm(s); and
- Domain specific mathematical model referred to as a template.

The major challenges in building any model are the validation of its application and the conclusions drawn from its use.

### 1.3.3 Exploring and Understanding the Solution Space

In model-based design, typically a designer has to use models of varying accuracy, completeness and fidelity. Hence, the ability to rapidly identify a solution space within which various designs can be explored is important. A strategy for identifying and exploring a possible solution space, a tailored computational environment created to solve the DSPs (Mistree, et al., 1990; Mistree, et al., 1991; Mistree et al., 1993; Mistree, et al., 1992; Reddy, et al., 1996) includes:

1. Discover regions where feasible designs exist based on satisfying the system constraints and bounds or where feasible designs might exist by minimizing the constraint violation, according to Smith and co-authors (Smith, et al., 2014).
2. Frame the feasible design space extremities from the neighborhood of the feasible or near feasible regions using a preemptive (lexicographic minimum) representation of the goals in a higher order search, according to Smith and co-authors (Smith, et al., 2014).
3. Having framed the space and the zones of greatest interest, move between the extremes generating deeper understanding and exploring tradeoffs using an Archimedean (weighted sum) formulation of the goals, according to Smith and co-authors (Smith, et al., 2014).

In dissertation all three steps are included and exercised, Steps 1 - 3 are presented in Chapter 4. A variety of tools and methods are appropriate in each step and these draw on a variety of mathematical foundations. However, obtaining feasible designs for a complex system is not an easy process especially when nonlinearities (dynamic operability model, Chapter 5, Section 5.2.) and overly tight constraints (reconfiguration model, Chapter 6, Section 6.4) can limit design opportunity.

Process knowledge, confidence and utility increase over time by exercising these three steps, Figure 1.10, and meet the recommended decision. The decisions are made through a series of diverging, synthesizing and convergent decision-making processes (Marston, 2000). The tool that is used in dissertation to support different design decisions is explore borrowed from XPLORE (Mistree, et al., 1990; Mistree, et al., 1991; Mistree, et al., 1993; Mistree, et al., 1992; Reddy, et al., 1996) in order to represent complementary design space and aspiration space exploration. XPLORE is a randomized method that is used in this work and described reference (Aird and Rice, 1977).

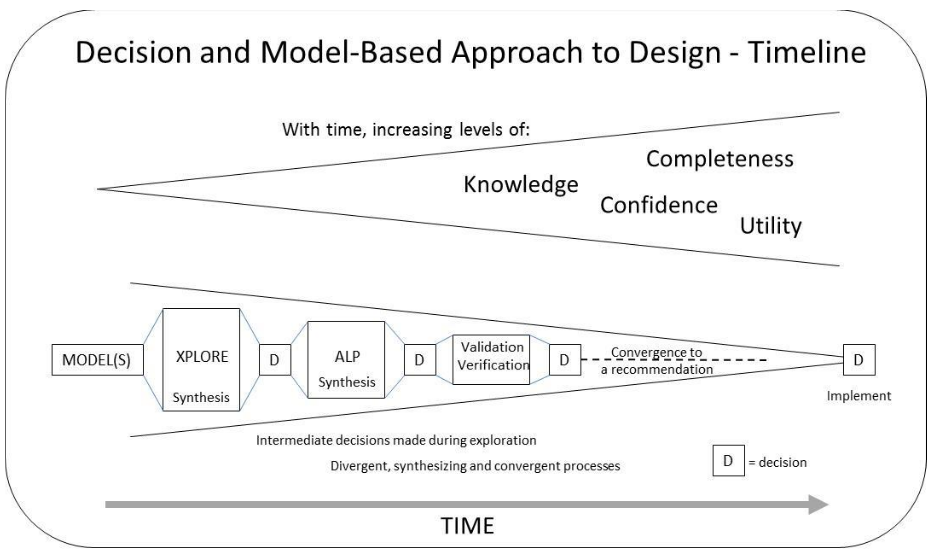


**Figure 1.10. Modelling and Decision Timeline**

Solution space exploration is an iterative process. As understanding of the solution space increases the confidence of the decision maker naturally grows, Figure 1.10. According to Smith and co-authors (Smith, et al., 2014), various methods may be applied to conduct a post-solution analysis of the data generated including visualization through the use of various plots.

### 1.3.4 The Validation Square

As mentioned earlier design is fundamentally a decision-making process and usefulness of decisions is proportional to a designer confidence. The validity of design decisions is proven with respect to its purpose. According to Seepersad and co-authors (Seepersad, et al., 2005), the Validation Square is a framework for validating design methods. Hence, validation square is used in the dissertation. In this framework, the utility of a design method is related to the correctness of design solutions, and whether the design solutions are produced efficiently with adequate operational performance according to Smith and co-authors (Smith, et al., 2014). The Validation Square consists of two main constructs structural validity and performance validity, Figure 1.11.

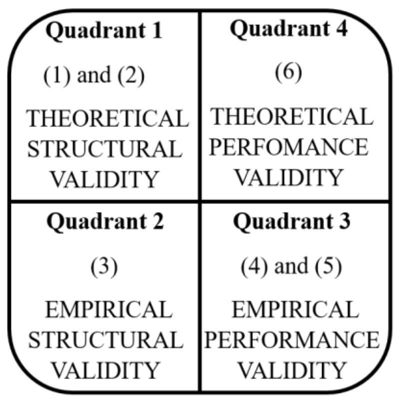


**Figure 1.11. Validation Square (Seepersad, et al., 2005)**

According to Smith and co-authors (Smith, et al., 2014), effectiveness of design method is a three-step process (1) accepting the individual constructs constituting the method; (2) accepting the internal consistency of the way the constructs are put together in the method; and (3) accepting the appropriateness of the example problems that will be used to verify the performance of the method. The validity of the method constructs considers the structural 'soundness' of the method in a more general sense, denoted as Theoretical Structural Validity in Figure 1.11. However, theoretical and empirical structural validity are evaluated qualitatively. Effectiveness of design method further implies three steps (4) accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s) (Smith, et al., 2014); (5) accepting that the achieved usefulness is linked to applying the method (Smith, et al., 2014); and (6) accepting that the usefulness of the method is beyond the case studies (Cagan and Vogel, 2002). Method is useful for some limited referees, denoted as Empirical Performance Validity. Similarly, the method is useful beyond some limited referees, i.e., useful in a more general sense, denoted as Theoretical Performance Validity.

### 1.3.5 Accounting for Uncertainty

Two main approaches are available in accounting for uncertainty (1) reducing uncertainty itself, not considered in this dissertation, and (2) second approach is designing a system to be insensitive to uncertainty without reducing or eliminating the source of uncertainty, robust design. Another name for robust design is parameter design due to the fact that it is used to make the system response insensitive to uncontrollable system input variations, thus improving the quality of a designed product (Choi, 2005). However, parameter design alone does not always leads to sufficiently high quality. Further improvement is achieved by controlling the source of variations which is associated with higher cost. Design at lower cost by sacrificing the achievement of optimal performance is the reason why the robust design approach is introduced to design.

Typically, design parameters are divided into three categories (1) control factors, (2) noise factors, and (3) responses. Control factors are parameters that designer can adjust. Noise factors are exogenous uncontrollable parameters that affect the performance of a system, process, product or service, Choi (Choi, 2005). Responses are performance measures of the product or process, Choi (Choi, 2005). The sources of uncertainty reside in system design models, based on which designers make their decisions. However, there are other sorts of uncertainty in the design of NES that cannot be managed or directly configured in parameters such as uncertainty due to assumptions in models and/or propagated uncertainty in multiscale simulation chains. It is important for designers to identify where a source of the uncertainty resides in a system model in order to employ an appropriate uncertainty management method (Choi, 2005).

In this dissertation, the author is accounting for uncertainty by managing uncertainty, designing a system to be insensitive to uncertainty without reducing or eliminating the source of uncertainty, robust design. There are different types of robust design associated with managing uncertainty in (1) uncontrollable parameters (Robust Design Type I); (2) controllable parameters (Robust Design Type II); (3) system functions (Robust Design Type III); and (4) design and analysis of process chain (Robust Design Type IV). Managing different types of uncertainty in the design of NES is explained in Milisavljevic (Milisavljevic, 2015).

Goals and focus in this dissertation, Section 1.4.1, identified gaps, Section 1.4.2, hypothesis and research questions, Section 1.4.3, identified contributions, Section 1.4.4, and identified gaps for a way forward, Section 1.4.5, are presented in the next section.

## 1.4 Goals and Focus in Dissertation, and Identifying Research Gaps for Transition to Industry

Discussion of motivation, Section 1.1, background and frame of reference, Sections 1.2 and 1.3, is introduced, and the problem addressed and major deliverables in the dissertation, Section 1.4, are presented. In this dissertation, the focus is on adaptable concurrent, operable, and reconfigurable design, Section 1.1.2, which is anchored in the concurrent design of both mechanical and control system, Section 1.2.1, concept exploration, Section 1.2.2, and decision-making at early stages of design, Section 1.2.3. The problem addressed in this dissertation is presented in Section 1.4.1. The focus in this dissertation is presented by listing the fundamental questions in Section 1.4.2. Contributions from this work are presented in Section 1.4.3. Lastly, the main research gaps for a way forward are introduced in Section 1.4.4.

### 1.4.1 Problem to be addressed - Computational Framework for Design of Smart Manufacturing Systems

The primary objective is to create a new knowledge, make a transformative influence in the design of networked engineering systems adaptable to ambitious market demands, and to accommodate the Industry 4.0 design principles.

The computational framework, Design for Dynamic Management, proposed as a support to adaptable concurrent design, system operability analysis, and reconfigurability of multiple elements in the system. This is achieved by (1) adaptable and concurrent design, flexibility in selection of design parameters and concurrent design of the mechanical and control systems, without a domain knowledge, (2) operability analysis, determine the functionality of the system in the presence of change, and (3) reconfiguration strategy, reestablish connectivity and allow reconfiguration among multiple elements in the system.

Given that overall design requirements are established and analysis programs exist, the principal motivation in the dissertation is to establish a computational framework that is suitable for the design of **low-cost** and **high-quality** networked engineering systems **adaptable to ambitious market demands** in the context of **Industry 4.0**.

In order to achieve this goal, a method for adaptable design, based on SoV modeling and compromise DSP (Mistree et al., 1993), is proposed, Quadrant 1 in Figure 1.12; operability analysis of NES, based on operability analysis, cDSP, and minimum time control, Quadrants 2 and 3 in Figure 1.12; and reconfiguration strategy of NES, based on cDSP and game theory, Quadrant 4 in Figure 1.12.

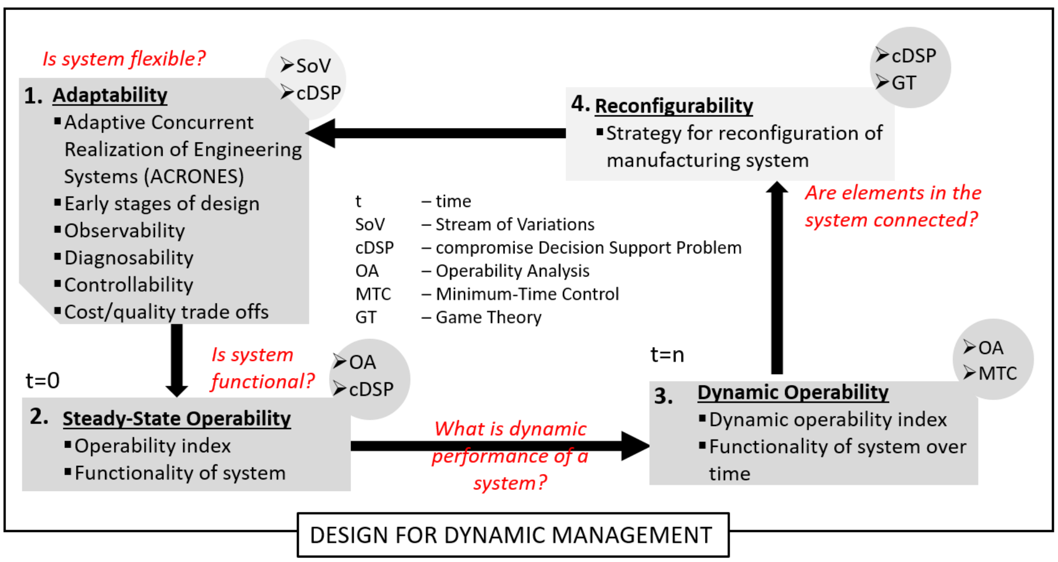


**Figure 1.12. Design for Dynamic Management Computational Framework**

### 1.4.2 Research Questions and Hypotheses in Dissertation

The primary interest is establishing a computational framework suitable for the design of low cost and high-quality networked engineering systems adaptable to ambitious market demands as a support to further digitization (smart manufacturing). As discussed in previous sections, dynamic changes in the market due to wide variations in customer needs lead to mass customization where enterprises have to be capable to adjust the manufacturing processes according to the wide variations of product design and substantial change of product scale. On the other hand, global competition requires enterprises not only to provide the cost-effective manufacturing processes but also to improve the quality of product and shorten time to market. Digitization of networked manufacturing systems (NMSs) is one technology that is increasingly being adopted to respond to changes in the market. Hence, the need for design methods to design a system adaptable to dynamic changes in the market. Accordingly, the primary objective of the proposed research is to create a new knowledge, make a transformative influence in the design of networked engineering systems adaptable to ambitious market demands, and to accommodate the Industry 4.0 design principles Development of the computational framework, Design for Dynamic Management, will be accomplished through (1) adaptable and concurrent design, inserting flexibility in selection of design parameters and concurrent design of the mechanical and control systems, without a domain knowledge, (2) operability analysis, determining the functionality of the system in the presence of change, and (3) reconfiguration strategy, reestablishing connectivity among elements in the system. Design for Dynamic Management is a decision-based multi-sensory design where design thinking, design strategy and innovation management is integrated to design a system adaptable to dynamic changes in the market. Given these goals, the key question to be addressed in the dissertation is presented as:

***Primary Research Question.*** *In the context of Industry 4.0 what is the computational framework that facilitates the decision-based design of networked engineering systems adaptable to ambitious market demands as a support to further digitization?*

The key question defines the scope and goals of the research and several research objectives are reflected. By using term decision-based design one phenomena is considered; diverse models to support the implementation of smart manufacturing features, digital thread, and digital twin; smart manufacturing features of flexible production, big data analysis at real time, and establishing connectivity among elements in the system; and Industry 4.0 as current trend of automation and data exchange in manufacturing technologies where foundational capabilities are wired interconnected world, abundant data storage and computing power, sensors and sensor fusion, the internet of things (IoT), cloud computing, cyber-physical systems, and smart factories (includes machine learning). However, this question does not reflect the deeper concern of design evolution and need to design a system to be adaptable to dynamic and ambitious market demands as a support to smart manufacturing. The foundation of the proposed computational framework is SoV modeling and compromise DSP, operability analysis, and reconfiguration strategy, Section 1.2. The key question expressed as three major research questions as listed below.

***Research Question 1.*** *What is the computational framework in the design method that facilitates adaptable design in the realization of networked engineering systems?*

***Research Question 2.*** *What is the computational framework in the design method that facilitates dynamic change in the requirements in the realization of functional networked engineering systems?*

***Research Question 3.*** *What is the reconfiguration strategy for reestablishing connection among elements in the system in the realization of networked engineering systems to remain competitive on the market?*

To answer the first research question, it is necessary to perceive the mechanical and control system concurrently and insert flexibility in selection and determination of values of design parameters in the design of NES. Further, to answer the second research question, it is necessary to establish operability and disturbance spaces, examine system performance in the presence of change, and examine the dynamic performance of the system in the presence of change. Finally, to answer the third question, there is a need for exploration and understanding of different reconfiguration strategies of a machine tool, inspection system, and manufacturing system altogether in order to remain competitive on the market with the low-cost process and high-quality product.

***Adaptable Concurrent Design of Networked Engineering Systems.*** In this section, the first research question is addressed. The first research question is addressed in two ways (1) determining requirements of adaptable design, and (2) determining main mechanical and control system drivers and their relation in order to achieve the concurrent design. The first research question is expressed as:

***Research Question 1.*** *What is the computational framework in the design method that facilitates adaptable design in the realization of networked engineering systems?*

***Sub-Research Question 1.*** *What is the algorithm that enables identification of the adaptable design of networked engineering systems?*

***Sub-Research Question 2.*** *What are the mechanical and control system drivers and is the computational framework in the design method that facilitates concurrent design?*

***Hypothesis for Research Question 1.*** *Design of mechanical and control system concurrently while accounting for different types of uncertainty and extensive (robust) solution space exploration facilitates the adaptable design of networked engineering system.*

***Sub-Hypothesis for Sub-Research Question 1.*** *Inserting flexibility in selection and determination of values of design parameters at design time facilitates the adaptable design of NES.*

***Sub-Hypothesis for Sub-Research Question 2.*** *Determining the mechanical and control system drivers and their mutual relations creates common ground for concurrent design and provides insights into NES.*

As described above, the Research Question 1 is separated into two supporting research questions. To answer Sub-Research Question 1, Sub-Hypothesis 1 is tested and verified. To answer Sub-Research Question 2, Sub-Hypotheses 2 is tested and verified. In Chapter 2, Section 2.1, some background knowledge related to the mechanical and control system drivers in the design of NES is presented. Hypothesis 1 is introduced in Chapter 3 and verified in Chapter 4. The test example is the 2-D panel assembling process in three stations, Chapter 3, Section 3.1.3.

***Operability Analysis of Networked Engineering Systems.*** In this section, the second research question is addressed. The second research question is addressed in two ways (1) determining system functionality in the presence of change, and (2) determining a dynamic performance of the system in the presence of change. The second research question can be expressed as:

***Research Question 2.*** *What is the computational framework in the design method that facilitates dynamic change in the requirements in the realization of functional networked engineering systems?*

***Sub-Research Question 1.*** *What is the algorithm that enables identification of the system functionality in the presence of change?*

***Sub-Research Question 2.*** *What is the algorithm that enables identification of the system dynamic performance in the presence of change?*

***Hypothesis for Research Question 2.*** *Determining input ranges (operability and disturbance spaces) that give desired solution range of functional system design at steady-state and dynamic state that will allow a system to adjust and stabilize in presence of change.*

***Sub-Hypothesis for Sub-Research Question 1.*** *Determining desired output space and available input space will give us information under which conditions system is functional even in the presence of change.*

***Sub-Hypothesis for Sub-Research Question 2.*** *Determining dynamic available input space gives us a fraction of operating ranges (if a system can transit and stabilize even in the presence of change) that can be achieved within the response time.*

As described above, the Research Question 2 is separated into two supporting research questions. To answer Sub-Research Question 1, Sub-Hypothesis 1 is tested and verified. To answer Sub-Research Question 2, Sub-Hypotheses 2 is tested and verified. In Chapter 2, Section 2.2.3, some background knowledge related to operability analysis in the design of NES is presented. Hypothesis 2 is introduced in Chapter 3 and verified in Chapter 5. The test examples are 2-D panel assembling process in three stations, and continuous stirred tank reactors, Chapter 3, Sections 3.1.3 and 3.1.4.

***Reconfiguration Strategy of Networked Engineering Systems.*** In this section, the third research question is addressed. The third research question is addressed in two ways (1) determining reconfiguration strategy of the machine tool as part of the manufacturing system, and (2) determining reconfiguration strategy of inspection system as part of the manufacturing system. The third research question can be expressed as:

***Research Question 3.*** *What is the reconfiguration strategy for reestablishing connection among elements in the system in the realization of networked engineering systems to remain competitive on the market?*

***Sub-Research Question 1.*** *What is the reconfiguration strategy of the machine tool in the networked engineering system?*

***Sub-Research Question 2.*** *What is the reconfiguration strategy of the inspection system in the networked engineering system?*

***Hypothesis for Research Question 3.*** *Machine tool reconfiguration followed by the inspection system reconfiguration will allow reconfiguration of the manufacturing system and reestablishing connection among elements in the system.*

***Sub-Hypothesis for Sub-Research Question 1.*** *Determining characteristics and requirements of operational stations (machine tools and machining operations) in order to reconfigure and accommodate to rapidly changing requirements (product design and product scale).*

***Sub-Hypothesis for Sub-Research Question 2.*** *Determining characteristics and requirements of the inspection system (sensors and sensing operations) in order to reconfigure and accommodate to rapidly changing operational stations (machine tools and machining operations).*

As described above, the Research Question 3 is separated into two supporting research questions. To answer Sub-Research Question 1, Sub-Hypothesis 1 is tested and verified. To answer Sub-Research Question 2, Sub-Hypotheses 2 is tested and verified.

In Chapter 2, Section 2.2.2, some background knowledge related to reconfiguration strategy in design of NES is presented. Hypothesis 3 is introduced in Chapter 3 and verified in Chapter 6. The test examples are 2-D panel assembling process in three stations, continuous stirred tank reactors, and transmission box in vehicles use, are presented in Chapter 3, Section 3.1.3.

The primary research question and secondary research questions are revisited in Chapter 7, Section 7.2, in order to verify the proposed hypothesis and research questions. Each of the hypothesis for research questions is verified through validation square, Tables 7.2 - 7.4.

### 1.4.3 Contributions in Dissertation

The hypotheses and sub-hypotheses, taken together, frame the research presented in the dissertation and define contributions from the research. The expected contributions from the dissertation are the following:

***Expected Contributions related to Hypothesis 1.*** *Adaptable and Concurrent Design of Networked Engineering Systems*

- Identifying mechanical and control system drivers and their relations in concurrent design,
- Build in flexibility in selection and determination of values of design parameters in both systems,
- Managing the structure of the high-complexity mathematical problem,
- Creating effective and efficient decision network structure as a decision support, and

- Integration of process- and product-related decision model in the comprehensive model.

***Expected Contributions related to Hypothesis 2.*** *Operability Analysis of Networked Engineering Systems*

- Framing operability/disturbance space without domain knowledge,
- Operability analysis of any engineering systems, and
- Managing system functionality due to change in the requirements.

***Expected Contributions related to Hypothesis 3.*** *Reconfiguration Strategy of Networked Engineering Systems*

- Strategy for Reconfiguration of Manufacturing System (RMS),
- Strategy for Reconfiguration of Manufacturing Tool (RMT), and
- Strategy for Reconfiguration of Inspection System (RIS).

### 1.4.4 Identifying Gaps for Way Forward

The principal goal in the dissertation is developing and integrating design methods to design a system adaptable to dynamic changes in the market as a support to further digitalization of manufacturing systems (smart manufacturing). Further, the main motivation is developing and integrating design methods to design a system adaptable to dynamic changes in the market as a support to further digitalization of manufacturing systems (smart manufacturing).

Identified research gaps in the dissertation for future work are:

***Research Gap 1.*** *Knowledge-Based Decision-Based Design Ontology*. There is a value to learn how knowledge can be captured and reused in the design of networked, multidisciplinary engineering systems. The goal is creating the scientific and educational foundation for multidisciplinary knowledge exchange in the design of NESs that will transform the way systems, a product-service system is designed and form a critical component of an enterprise's intellectual capital.

***Research Gap 2.*** *Decision-Based Design Platform.* Defining decision support problem construct, decision template, and ontology in order to reach platformization as a support to digitalized manufacturing. The requirements for a platform to support human decision making and to transit to the industry are defined users template (creator, editor, and implementer), define a flowchart of decision-based design, and ensuring knowledge-based decision support.

Requirements for knowledge-based decision support are defining rule-based knowledge exchange between different domains (such as mechanical and electrical engineering), determining taxonomy from different domains, interfacing domain ontologies, and converting mechanical into the electrical analogy.

***Research Gap 3.*** *Integrating Cyber-Physical-Social System (CPSS) in the Platform.* Industrial social system and product/service system development where Cyber-Based Design (CBD) will be integrated with social networks. The requirement is to develop cyber-social design decision network that will accommodate social aspect.

The future work is further discussed in Chapter 7, Section 7.4, where the Research Gap 1 is discussed in Section 7.4.1, the Research Gap 2 is discussed in Section 7.4.2, and the Research Gap 3 is discussed in Section 7.4.3.

The overview of the dissertation and the validation strategy is presented in the next section.

## 1.5 Overview and Validation Strategy of Dissertation

In the design of networked engineering systems there are subjective elements involved in decision making that reflects the initial design stage of framework implementation; therefore, there is a need to undertake the validation and verification of a method/result due to the fact that a development of a method includes many abstract elements and there is no unique answer.

The "Validation Square", Section 1.3.3, is a method where designers build confidence in the utility of methods and examples that are used to verify the method (Pedersen and Emblemsvag, 2000). Further, the validation square is used to determine whether the method provides correct design solutions regarding structural validity and regarding performance validity (Choi, 2005).

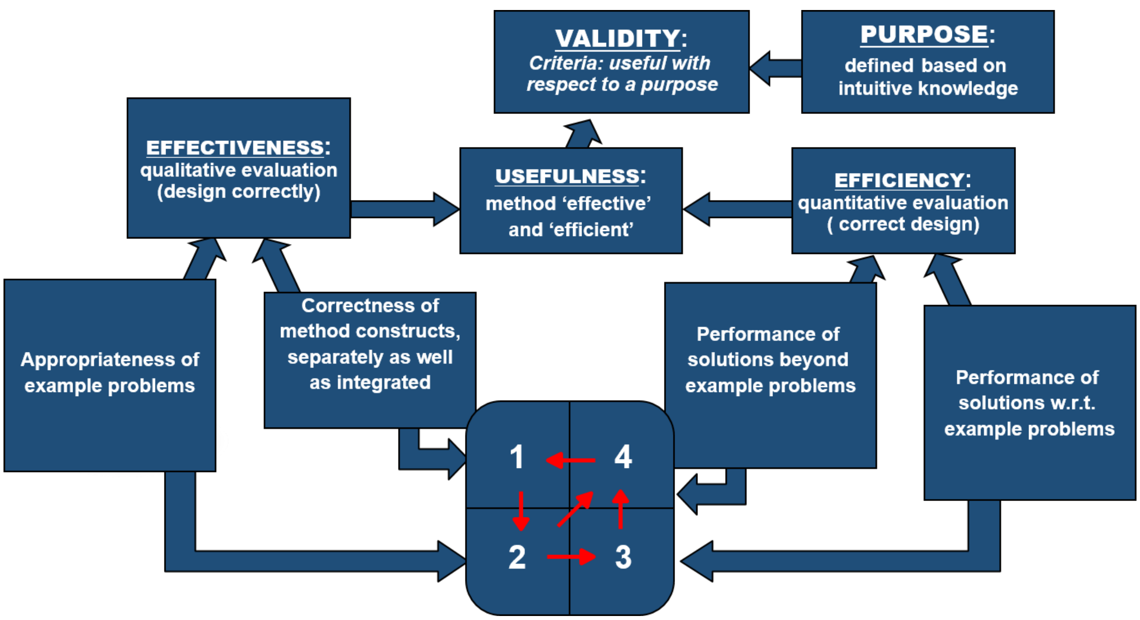


**Figure 1.13. Validation Square (Pedersen, et al., 2000)**

The validation square is the process of validation, Figure 1.13, and the validation quadrants are:

- ***Quadrant 1.*** *Theoretical Structural Validity*. *E*xamining the structural/ logical validity and overall consistency of the proposed computational framework.
- ***Quadrant 2.*** *Empirical Structural Validity*. Includes building the confidence of the example problems chosen to verify a suggested design computational framework.
- ***Quadrant 3.*** *Empirical Performance Validity*. Used to build confidence in the applicability of a computational framework for the example problems that are chosen.
- ***Quadrant 4.*** *Theoretical Performance Validity*. Building confidence in the general use of the computational framework and determining is it useful for other problems beyond the example problems.

In this dissertation, the validation square is adopted as a guideline for validating the Design for Dynamic Management. Planned tasks for the validation of the dissertation are summarized and presented in Figure 1.14.

*Theoretical Structural Validation Tasks*

- Critically review the relevant literature and identify research opportunities, Chapter 2.
- Justify the three hypotheses are logically formulated and appropriately cover the research opportunities, Chapter 2.
- Discuss the decision-based design of NES in the context problem discussion and formulation, mathematical background of proposed models, the computational framework, design for dynamic management, of adaptable and concurrent design,

operability analysis, and reconfiguration strategy are constructed to verify the hypotheses in intellectual and methodological aspects, Chapter 3.

- Identify utility, constraints, application domains for the developed computational framework, design for dynamic management, Chapter 3.

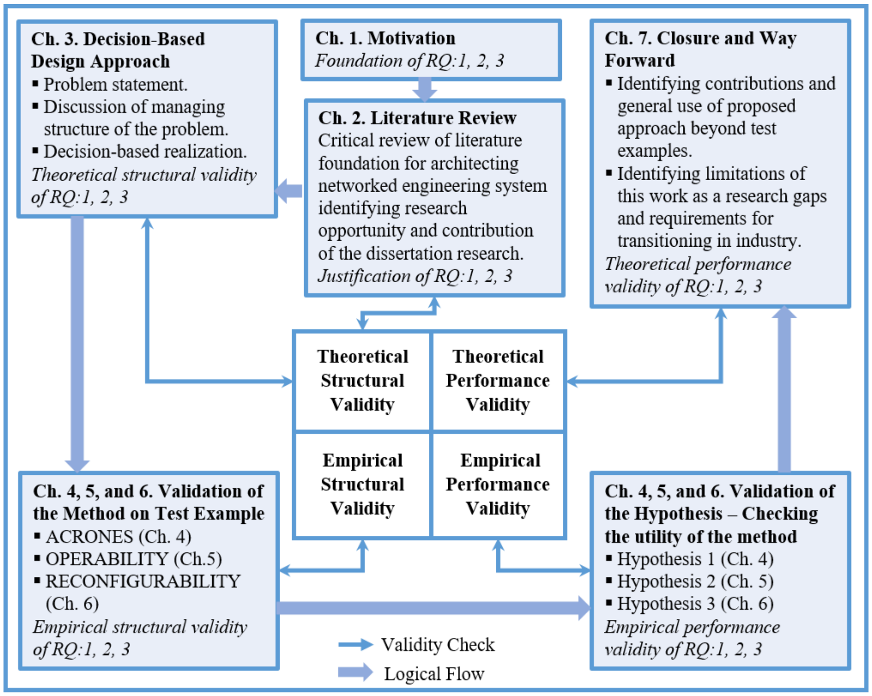


**Figure 1.14. Validation Strategy of Dissertation**

*Empirical Structural Validation Tasks*

- Discuss the adaptability models challenges, Test Example 1, and testing the Hypotheses 1, Chapter 4.
- Discuss the operability models challenges, Test Example 2, and testing the Hypotheses 2, Chapter 5.
- Discuss the reconfigurability models challenges, Test Example 3, and testing the Hypotheses 3, Chapter 6.
- Prove that data is useful for testing the hypotheses.

*Empirical Performances Validation Tasks*

- Validate Hypotheses 1 based on the results in the adaptability model, Chapter 4.
- Validate Hypotheses 2 based on the results in the operability models, Chapter 5.
- Validate Hypotheses 3 based on the results in the reconfigurability models, Chapter 6.

*Theoretical Performances Validation Tasks*

- Prove the hypotheses are valid but limited for the design of networked engineering system, Chapter 7.
- Identify research gaps presented in future work and will be further addressed where the proposed computational framework will be transferred in the platform, and expended to cyber-physical-social systems that will make it useful for examples beyond presented one in the dissertation, Chapter 7.

The organization and a roadmap of the dissertation is presented in Figure 1.15.

***Chapter 1.*** The motivation and foundation are discussed for novel architecture where architecting networked engineering system accounting for adaptable and concurrent, operable, and reconfigurable design is considered. The principal goal, research questions, and hypotheses are introduced. The expected contributions are summarized, research gaps for future work are introduced, and a validation strategy is established in the dissertation.

***Chapter 2.*** The theoretical foundations for adaptable and concurrent design, operability analysis, and reconfiguration strategies are introduced and discussed. Relevant literature in each of these research areas is referenced, discussed, and critically evaluated in order to prove theoretical structural validity. The availability, strengths, and limitations of methods and constructs are discussed, which is a foundational design of NES, the stream of variation modeling in engineering design of NES, and to identify research opportunities addressed in the dissertation.

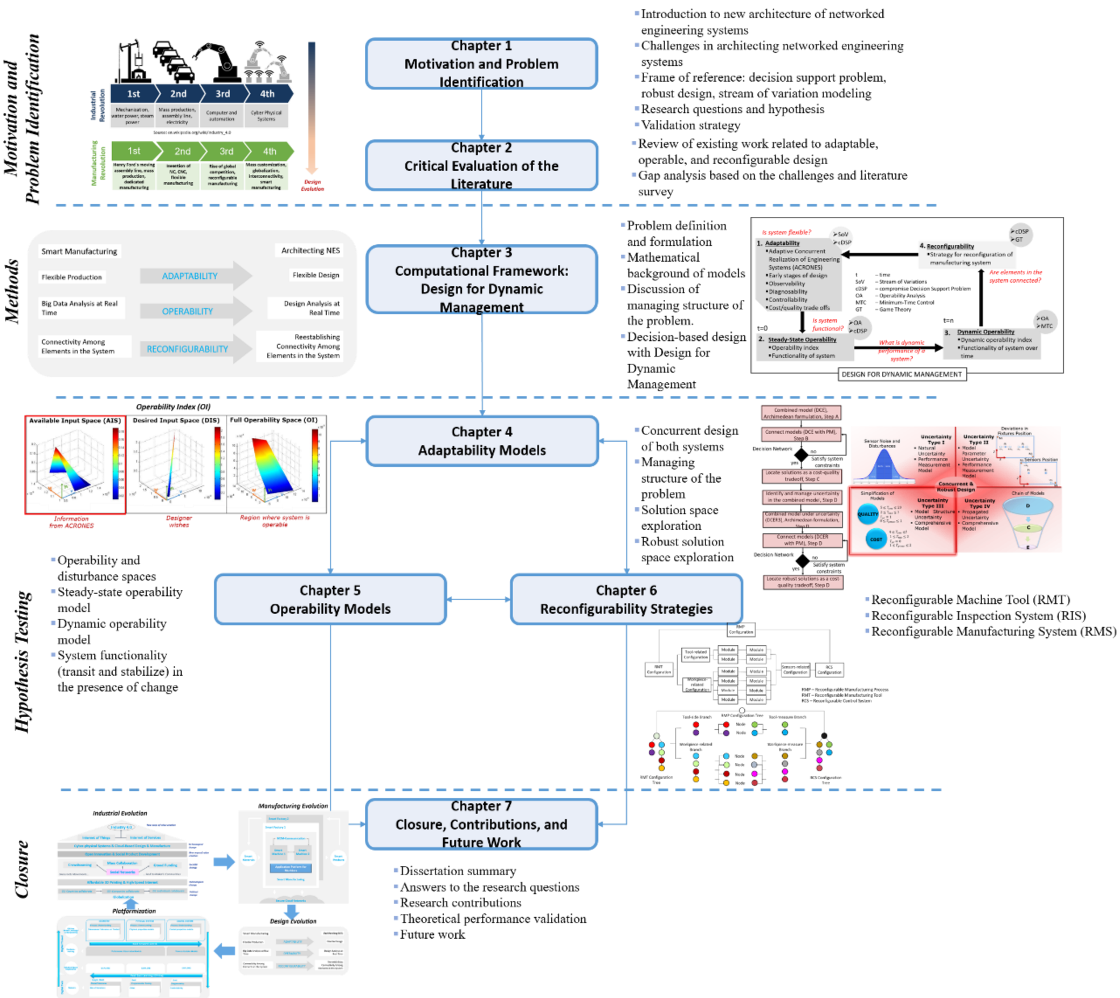


**Figure 1.15. A Roadmap and Overview of the Dissertation**

***Chapter 3.*** A problem definition of the design of NES is introduced, the mathematical formulation is considered as a background for later chapters, how to structure and partition mathematical problem of high complexity, and how to create an appropriate decision network structure. Further, desired NES characteristic are postulated and a computational framework, Design for Dynamic Management is presented.

***Chapter 4.*** The adaptability models are considered, (i) without uncertainty (D), and (ii) with uncertainty where its effect on a designer`s decision is analyzed through solution space exploration. Further, characteristics of these models, compromise DSP formulation, and a strategy to find appropriate solutions are proposed. A numerical example is used to verify the utility of the decision models that are proposed. Structural and performance validity of adaptability models follows validation square structure. In summary, this chapter is uniting the material from Chapters 1, 2, and 3 together in order to answer the Research Questions 1.

***Chapter 5.*** The operability models are considered and its influence on decision making through observation of operability space. The inclusion of different types of uncertainties is considered and its effect system operability is analyzed through disturbance space exploration. Further, characteristics of these models, compromise DSP formulation, and a strategy to find appropriate solutions are proposed. Numerical examples are used to verify the utility of the performance operability models that are proposed. Structural and performance validity of operability models follows validation square structure. In summary, this chapter unifies the material from Chapters 1, 2, 3, and 4 together in order to answer the Research Questions 2.

***Chapter 6.*** The inclusion of different reconfiguration strategies are considered and its effect on the reconfiguration of the manufacturing system is analyzed through strategies exploration. Further, characteristics of models, compromise DSP formulation, and a strategy to find appropriate configuration/solutions is proposed. Numerical examples are used to verify the utility of the reconfiguration strategies. Designer insights are taken into account in these numerical examples. Analysis of the results of these numerical studies is used to demonstrate the practical applicability of the proposed approach. In summary, this chapter unifies the material from Chapters 1, 2, 3, and 5 in order to answer the Research Questions 3.

***Chapter 7.*** The summary of the dissertation followed by research questions and validation of the hypotheses are presented. Further, research contributions and achievements are discussed. Nevertheless, the primary motivation in the dissertation is to frame the problem, identify research gaps and define research questions that will be further addressed in future research in order to expand proposed computational framework and make it applicable to other examples beyond the networked engineering systems.

## 1.6 Synopsis of Chapter 1

In this chapter, the problem of design of networked engineering systems (NES), research gaps, and the research questions worthy of investigation are introduced. The motivation for the computational framework, Design for Dynamic Management, is introduced through discussion on two topics (1) how a change of demands changed the industry and how manufacturing processes evolved, and (2) frontiers in Industry 4.0 and how challenges in smart manufacturing systems are addressed through design. The background anchored in concurrent design, concept exploration, and decision-making at the early stages of design is established. The frame of reference built in Stream of Variation (SoV) modeling, the compromise Decision Support Problem (cDSP) construct, solution space exploration, verification and validation, and robust design are presented. Further, in this dissertation the foundation is created for a way forward by framing the problem, identifying the research gaps and questions worthy of investigation.

New trends in production engineering and design are introduced in Section 1.1. Further, the background for Design for Dynamic Management is presented in Section 1.2, followed by concept exploration and making design decisions in the early design stages. The scope of the dissertation of adaptable, operable and reconfigurable design, Section 1.3, Stream of Variation (SoV) modeling, the compromise Decision Support Problem (cDSP) construct, solution space exploration, verification and validation, and robust design are presented. In Section 1.4, the research questions and corresponding hypotheses are established. Further, the contributions of the dissertation are summarized followed by research gaps that are identified in the dissertation and further will be addressed as a way forward. The validation of the proposed hypotheses strategy is presented in Section 1.5. Evaluation of the structural soundness of the dissertation and answer research questions are performed by revisiting this chapter.

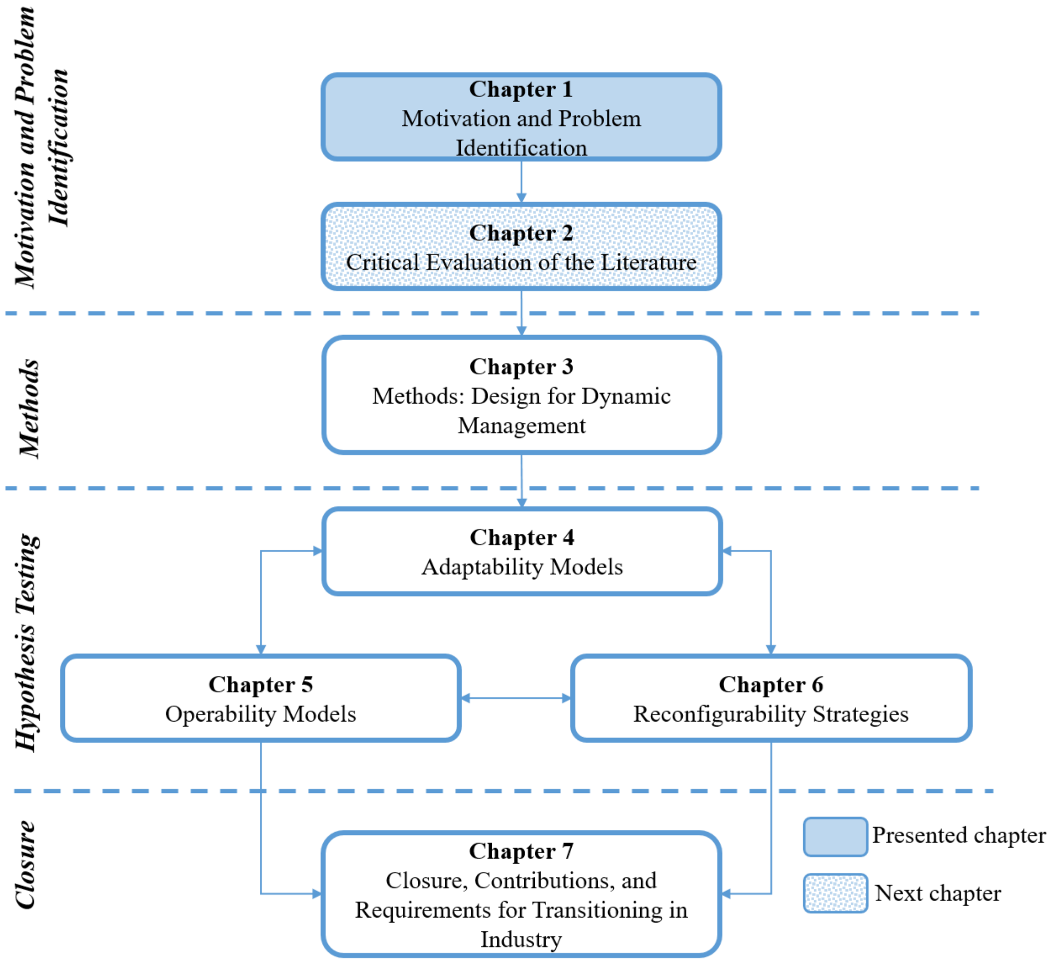


**Figure 1.16. Organization of the Dissertation – Presented and Next Chapter**

In Chapter 2, Figure 1.16, literature review of existing work related to adaptable and concurrent design, operability analysis, and reconfiguration strategy is presented in Section 2.1 – 2.3. Further, gap analysis based on the challenges and literature survey is presented is presented in Section 2.4.

# CHAPTER 2

# CRITICAL REVIEW OF LITERATURE, GAPS, AND (POTENTIAL) RESEARCH OPPORTUNITIES

Main issues in the design of networked engineering systems are (i) adaptable and concurrent design, (ii) system operability, and (iii) system reconfigurability. Each of this issues has been studied rigorously. In this chapter, literature is reviewed regarding mentioned issues, research opportunities in this dissertation and the potential research opportunities that will be addressed in future work are located.

In this chapter, methods, and approaches related to the design of networked engineering systems (NES) are considered while accounting for system adaptability, operability, and reconfigurability. State of the art in adaptable and concurrent design, Section 2.1., system operability analysis, Section 2.2, and system reconfigurability, Section 2.3, are presented. Further, within system reconfigurability, strategies for reconfiguration of a machine tool, Section 2.3.1, reconfiguration of an inspection system, Section 2.3.2, and reconfiguration of the manufacturing system, Section 2.3.3, are presented. Capabilities of methods and approaches in the design of NES are critically evaluated with respect to the needs of adaptable and concurrent, operable, and reconfigurable design of NES, as introduced in Chapter 1, as a part of theoretical structural validation, see Figure 2.1. Research opportunities and potential research opportunities for future work are identified from these reviews, Section 2.4, that are further addressed in Chapters 4 – 6.

## 2.1 Adaptable and Concurrent Design

A multistage manufacturing process (MMP) refers to a system that consists of multiple operational stations, or components required to manufacture a product or perform a service, Shi and Zhou, 2009. Production in an MMP is a continuous process where the product is manufactured stage by stage and local variations at each stage as well as interactions amongst multiple stages affect the final product quality. Early analysis of manufacturing systems focused on material planning and control strategies. These strategies can be looked at as push, pull or hybrid depending on the method of releasing the production orders to individual stations. Materials requirement planning and Kanban control systems are well-known implementations of push and pull strategies respectively. Hybrid strategies incorporate features of both push and pull systems (Krishnamurthy, et al., 2004). Several authors have also studied the performance of these strategies in relation to the production volume and product variability (Spearman and Zazanis, 1992; Buzacott and Shanthikumar, 1993; Womack and Womack, 2003; Suri, 1998; Spearman and Hopp, 1996). While these studies assumed deterministic representations of the manufacturing process, researchers such as Altiok (Altiok, 1997), incorporated the stochastic modeling of manufacturing systems where the production function and inventory control were both emphasized. Gershwin, on the other hand, modeled assembly lines as 'transfer lines' and studied the effect in process time variability and buffer size between stages on the overall production rate and average in-process inventory, (Gershwin and Gershwin, 1994). While these methods are well known, they are not suited for use in the design of MMPs to achieve a specified quality.

Part manufacture and assembly are one of the largest applications of MMP. In these applications, the tools and sensors at each manufacturing stage ensure that the component or subassembly at that stage meets pre-specified design criteria. However, errors arising from tool wear, incorrect part fixturing, component failure, process uncertainties etc., and these propagate from state to stage and can cause degradation of overall product quality (Jiao and Djurdjanovic, 2010). One approach is to study the cause of accumulated errors in MMPs and reduce their effects on product quality (Jin and Shi, 1999). Another approach is to model the MMP as a dynamic system and consider parameters such as diagnosability and controllability to study the effect of sensor placement and tooling on the MMP (Ding, et al., 2003). Optimality can also be considered to determine appropriate system parameters to minimize an overall cost metric for an MMP (Ding, et al., 2003). Regardless of the approach, an understanding of the functional attributes of the mechanical and control systems that comprise the MMP and their effects on the properties of the MMP is necessary. In this study, the focus is on the dimensional quality as a product requirement and the design of the MMP to meet this requirement. The parameters of the mechanical system, namely the type, number, and the position of fixture locators, are assumed to be known. In addition, the parameters of the control system, namely the type, number, and the position of sensors and sensing stations are assumed to be known. The design question is how to select the appropriate number of sensors and their characteristics to guarantee that the cause of dimensional variations is diagnosable and to ensure that the overall system is controllable, i.e., that the effect of variations on the dimensional quality is eliminated.

The use of Stream-of-Variation (SoV) model in analyzing diagnosability and controllability of MMPs is demonstrated by different authors (Jin and Shi, 1999; Ding et al., 2000; Ding et al., 2002a, 2002b and 2002c). However, this analysis assumes that all model details are fixed, an assumption that is untrue at design-time. The requirement that the MMP be diagnosable and controllable affects the choice of several design variables, see Table 2.1.

**Table 2.1. Requirements List for Design of the MMP**

| Requirements | Type of Requirements | Type of Design Variables | Mechanical/ Control System Parameters |
|---|---|---|---|
| type of fixture locator | flexible | Integer | M |
| number of fixture locator | flexible | Integer | M |
| position of fixture locator | flexible | Continuous | M |
| type of sensors | flexible | Integer | C |
| number of sensors | flexible | Integer | C |
| position of sensors | flexible | Continuous | C |
| distribution of sensors | flexible | Boolean | C |
| type of sensing stations | flexible | Integer | C |
| number of sensing stations | flexible | Integer | C |
| programmable tooling control actions | flexible | Boolean | C |
| process diagnosability | fixed | Boolean | C |
| process controllability | fixed | Boolean | C |
| reducing overall cost | flexible | Integer | |
| improving dimensional quality of products | flexible | Continuous | |

An extensive literature survey documented by Milisavljevic (Milisavljevic, 2015), the key unresolved difficulties, see Table 2.2, are:

1. the appropriate selection of design parameters (Ding, et al., 2002a; Ding, et al., 2002b),
2. the need for concurrent design (Liu, et al., 2006),
3. integrating flexibility in the design itself (Mistree, et al., 1993),
4. achieving diagnosability and controllability simultaneously (Ding, et al., 2002c),

5. overcoming computational complexity (Xiao, 2003), and
6. developing a general method applicable to any type of MMP (Milisavljevic, 2015).

Key difficulties in MMP design have been addressed individually by several authors, Table 2.2. However, there is a need to address all difficulties in the design of MMP and develop a systematic method for the concurrent design and analysis of multistage manufacturing processes (Milisavljevic, 2015).

The gaps identified in this section are further recognized as research opportunities, see Section 2.4.1, that are further addressed in this dissertation in Chapter 4.

# Table 2.2. Overview Foundational Papers for Identifying Key Unresolved Difficulties in the Adaptable and Concurrent Design of MMPs

| Paper | Aspects | | | | | Methods | | | | | | | | Literature Evaluation | | | | | | | | | | | | Research Gaps |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Concurrent Design | Solving Multi-Objective Problems | Solution Space | Stream of Variation | Design of Control System | Collaborative Multidisciplinary | Model-Based Exploration through Decision Making | Objectives-Orientated Sensor Allocation by Multivariate Analysis | Compromise Decision Support Problem | State-Space Model Variation Propagation in | Diagnosability Analysis of MMP | Controllability Analysis of MMP | Cost-Orientated Sensors Distribution in Design of | Partitioning Problems on Few Stakeholders | Game Theoretical Approach for Coupling | Solution Space Exploration in Design of Complex Systems Solution Space | Model-Based Approach Implemented In DSIDES | Objective-Orientated Coupling Or Interactions in Design of MMP | Locating Ranges of Solutions Instead of | SoV for Systematic Analysis and Variation Propagation Control in | SoV For Fault Diagnosis in Design of MMP | SoV for Generic MMPs | Design of Diagnosable MMP by Use of SoV | Design of Controllable MMP by Use of SoV | Design of Cost-Optimal MMP by Use of SoV | |
| Xiao, A., et al. (2003) | * | | | | | * | | | | | | | | * | * | | | | | | | | | | | Concurrent design of a mechanical and a control system in design of MMP |
| Smith, W.F., et al. (2014) | | * | | | | | * | | | | | | | | | * | * | | | | | | | | | Solving complex mathematical problems |
| Liu, K., et al., (2006) | | * | | | | | | * | | | | | | | | | | * | | | | | | | | Finding range of solutions in design of MMPs |
| Mistree, F., et al. (1993) | | | * | | | | | | * | | | | | | | | | | * | | | | | | | Cost-quality tradeoff in solution space exploration |
| Jin and Shi (1999) | | | | * | | | | | | * | | | | | | | | | | * | | | | | | Generalized method that can fit any MMP, requirements, etc. |
| Ding, Y., et al. (2000) | | | | * | | | | | | | * | | | | | | | | | | * | * | | | | Generalized method that can fit any MMP, requirements, etc. |
| Ding, Y., et al. (2002) | | | | | * | | | | | | * | | | | | | | | | | * | | * | | | Observe diagnosability and controllability concurrently in design of MMP |
| Mantripragada, R., et al. (1999) | | | | | * | | | | | | | * | | | | | | | | * | | | | * | | Observe diagnosability and controllability concurrently in design of MMP |
| Ding, Y., et al. (2003) | | | | | * | | | | | | | | * | | | | | | | | | | | | * | Observe cost and process diagnosability and controllability in design of MMP |
| Shi, J., et al. (2009) | | | | | * | * | | | | | * | | | | | | | | | | * | | | | | Design of MMPs requires fusion of theories, tools and techniques from multiple disciplines to achieve utilization of information |
| Jiao, Y., (2012) | | | | * | * | | | * | | | | * | | | | | | | | | * | | | * | | Generalized method that can fit any MMP, requirements, etc. |
| Izquierdo, L.E., et al. (2007) | | | | | * | | | | | * | | * | | | | | | | | * | | | | * | | Observe process controllability and product quality concurrently in design of MMP |
| Mistree, F., et al. (1992) | | | * | | | | | | * | | | | | | | | | | * | | | | | | | Cost-quality tradeoff in solution space exploration |
| Apley, D., et al. (1998) | | | | | * | | | | | | * | | | | | | | | | | * | | * | | | Generalized method that can fit any MMP, requirements, etc |
| Smith, W.F., et al. (2015) | | * | | | | | * | | | | | | | | | * | * | | | | | | | | | Solving complex mathematical problems |
| Marston, M., et al. (2000) | | * | | | | | * | | | | | | | | | * | * | | | | | | | | | Solving complex mathematical problems |
| Milisavljevic, J., (2015) | * | * | * | * | | * | * | | * | * | * | * | * | | | * | * | * | * | | | * | * | * | * | Forward mentioned research gaps |

## 2.2 System Operability Analysis in Design

The bond between the design of the process and control of the process dictates from early 40`s, Ziegler and Nichols (Ziegler and Nichols, 1943), clearly delineate the limitations of control on a poorly designed process Georgakis and co-authors (Georgakis, et al., 2003).

The quote "Well designed plant is also a well-controlled one" is recognized by many researchers. In fact, considering operability issues early in the design stage become additional motivation for chemical suppliers to minimize variation of their products, Downs and Ogunnaike (Downs and Ogunnaike, 1995) according to Georgakis and co-authors (Georgakis, et al., 2003).

The bridge between design and control is introduced by operability analysis where systematical exploration of the beneficial as well as a detrimental interaction between process and control designs is taking place. A precise measure of operability is necessary in order to effectively accomplish this interaction.

> "An operability measure should quantify the inherent ability of the process to move from one steady state to another and to reject any of the expected disturbances in a timely fashion with the limited control action available" Georgakis and co-authors (Georgakis, et al., 2003).

Operability analysis is classified into two categories linear-based, and nonlinear-based methods.

***Linear-Based Methods.*** Linear methods are developed to address the problems of multiple-input-multiple-output (MIMO) systems, without any explicit account of the limited range available to the input variables (Georgakis, et al., 2003). Morari (Morari, 1983) identified the relationship between the invertibility of the transfer function matrix of a system and its resilience, where factors that prevent inversion of the process are (I) right-half-plane (RHP) zeros, (2) time delays, (3) constraints on the input variables, and (4) model uncertainty. In addition to Morari`s invertibility of the transfer function matrix there are other linear-based methods that are worthy of mentioning Georgakis and co-authors (Georgakis, et al., 2003):

1. Singular Value Decomposition (see e.g., Moore, 1986; Grosdidier and Morari, 1986; Cao, et al., 1996) in addressing various aspects of control problems (control variable pairing, optimal sensor location, robust controller design, and resiliency);
2. Relative Gain Array (RGA) gives a quantitative measure of control-loop interaction for multivariable systems (e.g., McAvoy, 1983; Grosdidier, et al., 1985; Zhu, et al., 1997);
3. Relative Disturbance Gain (Stanley, G., et al., 1985);
4. Block Relative Gain (Manousiouthakis et al., 1986);
5. Relative Sensitivity (Arkun, 1988); and
6. Closed-loop Disturbance Gain (Hovd and Skogestad, 1992).

Plant operability assessment was introduced by Swartz (Swartz, 1996) where solution obtained represents an upper bound on the performance of all linear stabilizing feedback controllers. Next year linear controllability analysis, based on optimal LTI control, was introduced by Chenery (Chenery, 1997). Lewin (Lewin, 1996) proposed a function of disturbance direction and frequency Georgakis and co-authors (Georgakis, et al., 2003).

***Nonlinear-Based Methods.*** Nonlinear methods are developed to utilize nonlinear models. Methods worth of mentioning are:

1. Flexibility Index (FI) for quantifying the steady-state operability of nonlinear processes (Swaney and Grossmann, 1985a). Further, FI approach with a basic assumption that the limiting points lie in the uncertain-parameter vertex directions (Swaney and Grossmann, 1985b), without assumption (Grossmann and Floudas, 1987), and extended version of FI approach for assessing the feasibility and flexibility of dynamic systems (Dimitriadis and Pistikopoulos, 1995) Georgakis and co-authors (Georgakis, et al., 2003);
2. Maintaining controllability of the plant with sufficient number of manipulated variables with enough range to keep the plant under nominal operating conditions when the disturbances affect the process (Fisher, et al., 1988);
3. Operability of the plant in the presence of disturbances through optimization (Bahri, et al., 1996). Further, addressing the dynamic operability using dynamic mixed-integer nonlinear programming (Bahri, et al., 1996);
4. An integrated design and control approach under parametric uncertainty and disturbances where flexibility aspects were incorporated in a multiperiod design subproblem coupled with a feasibility analysis of dynamic systems (Mohideen, et al., 1996);
5. Operability characteristics through dynamic simulations of the SISO control structures (Lyman, et al. ,1996);
6. Operability of C8TRs with exothermic reactions (Russo and Bequette, 1995 and 1998); and
7. Methods for the inherent steady-state operability of linear continuous processes (Vinson and Georgakis, 1998 and 2000), nonlinear processes (Subramanian and

Georgakis, 2000 and 2001), extended to dynamic operability analysis (Uztiirk and Georgakis, 2001), and examination operability characteristics of non-square systems (Subramanian, et al., 2001).

The main problem in the design of networked engineering systems to remain competitive in a global market is to accommodate dynamic and ambitious market demands. The challenges are dynamic changes, unexpected disturbances, variation in product design, and product scale change. These challenges create a need to fully examine the dynamical and control characteristics of a system in the design stage. It is evident that the current approaches, see Table 2.3, for the design of networked engineering systems, have certain limitations, and unresolved difficulties which are identified as the following research gaps:

- Expand operability analysis to fit any engineering system rather than plant design while framing the operability and disturbance spaces without prior domain knowledge and analyzing system functionality with change in the requirements in addition to disturbances (Georgakis, et al., 2003; Fisher, et al., 1988; Bahri, et al., 1996; Lyman, eta l., 1996; Russo, et al., 1995 and 1998; Subramanian, et al., 2000; Subramanian, et al., 2001 and 2001); and
- Expand dynamic operability analysis to the design of complex systems (multi-variable and different goals problems) and analyze dynamic performance of the system due to change in the requirements in addition to disturbances (Mohideen, et al., 1996; Uztürk and Georgakis, 1998).

**Table 2.3. Overview of Foundational Papers for Identifying Key Unresolved Difficulties in the Design of Networked Engineering Systems Regarding System Operability**

| | Paper | Georgakis, C., et all., 2003 | Fisher, W. R., et all., 1988 | Bahri, P. A., et all., 1996 | Lyman, P. R., et all., 1996 | Russo, L. P., et all., 1995 | Russo, L. P., et all., 1998 | Subramanian, S., et all., 2000 | Subramanian, S., et all., 2001 | Subramanian, S., et all., 2001 | Uztiirk, D., et all.., 1998 | Mohideen, M. J., et all., 1996 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Research Gaps | Expand operability analysis to fit any engineering system, framing the operability/disturbance spaces, analyzing system functionality with change in the requirements | | | | | | | | | Expand to design of complex systems and analyze dynamic performance | |
| Analysis | Feasibility Analysis of Dynamic Systems | | | | | | | | | | | * |
| | Operability Analysis of Dynamic Systems | * | * | * | * | * | * | * | * | * | * | |
| | Diagnosability and Controllability | | | | | | | | | | | |
| | Analyze of Error Propagation | | | | | | | | | | | |
| | Production Function and Inventory Control | | | | | | | | | | | |
| | Production Volume and Product Variability | | | | | | | | | | | |
| Methods | Operability Characteristics of Non-Square Systems | | | | | | | | | * | | |
| | Dynamic Operability Analysis | | | | | | | | | | * | |
| | Operability Characteristics through Dynamic Simulations | | | | * | | | | | | | |
| | Integrated Design and Control Approach under Parametric Uncertainty | | | | | | | | | | | * |
| | Optimization-based Operability | | | * | | | | | | | | |
| | Maintaining Controllability of the Process in the Presence of Disturbance | | * | | | | | | | | | |
| | Steady-State Operability of Nonlinear Processes | * | | | | * | * | * | * | | | |
| | Dynamic Modeling of Manufacturing System | | | | | | | | | | | |
| | Stream of Variation Modeling | | | | | | | | | | | |
| | Stochastic Modeling of Manufacturing Systems | | | | | | | | | | | |
| | Push and Pull Strategy | | | | | | | | | | | |
| Aspects | Operability | * | * | * | * | * | * | * | * | * | * | * |
| | Adaptability | | | | | | | | | | | * |

The gaps identified in this section are further recognized as research opportunities, see Section 2.4.2, that are further addressed in this dissertation in Chapter 5.

## 2.3 System Reconfigurability in Design

Reconfigurable Manufacturing System (RMS), is a complex system consisting of a series of connected workstations. With new manufacturing trends, RMS is requested to not only have the economic benefits of scale production but to quickly adapt to a dynamically changing manufacturing environment. Thus, it is designed to adjust capabilities and functions for several part families, while maximizing the use of existing resources to reconfigure or update the manufacturing process. The main elements of RMS are Reconfigurable Manufacturing Tool (RMT), Section 2.3.1, and Reconfigurable Inspection System (RIS), Section 2.3.2. RMT plays the role of manufacturing the blank or the intermediate product, while RIS performs the quality inspection on the intermediate product or final product. On the one hand, RMT and RIS consist of the modular components, such as the mechanical modules and the sensing modules. Further, all of RMTs in RMS is considered as the subsystem to perform the customized production, which is called Reconfigurable Production Subsystem. The RISs is formed into another subsystem, called Reconfigurable Inspection System, which is primarily responsible for providing full real-time detection. Facing the RMS multi-granular configuration, the reconfiguration takes place on a certain scale of time and space. According to the different time scales and concerns, the RMS configuration design is divided into module granularity, equipment granularity, and system granularity, Section 2.3.3.

### 2.3.1 Reconfigurable Machine Tool (RMT)

Enterprises recognized the reuse of the existing resource and the flexibility for the unpredicted environment has to be embraced in order to facilitate sustainable development. Hence, they become more aware of the profitability of reconfiguration and invested more in related emerging technologies for reconfigurable configuration. At present, the reconfigurable configuration design is mainly taking place in two fields: robot and manufacturing. In manufacturing, there are three reasons for forcing the reconfiguration: random failure, product variance, and demand fluctuation. However, the methods available for a conventional machine tool are not a match with Reconfigurable Manufacturing Tool (RMT), and there is a strong need to develop a unique configuration design methodology for RMT (Heisel and Meitzner, 2006). Improving responsiveness would result in improving the product quality on the expense of cost, which would support enterprises to gain more profits and attract more customers, leading to greater reconfiguration of the customized requirements (Youssef and ElMaraghy, 2006; Abdi, 2009; Goyal, et al., 2012; Wang and Koren, 2012). Further, in addition to reaching the target value of the conflicting goals the RMT configuration design is required to satisfy the functional constraints bounded by the manufacturing process such as the production rate or the delivery time (Dou, et al., 2009; Al-Zaher, et al., 2013; Puik, et al., 2017; Xia et al., 2017).

After reviewing some of the done work, the details of the research gap in the existing method are summarized in Table 2.4:

- Ability to scale capability and convert functionality (Andersen, et al., 2017);
- Effectively identifying the tasks from the part family (Koren, et al., 1999);
- Clearly modeling the descriptions of different configuration (Mpofu, et al., 2008);
- Systematically evaluating the configuration via multiple performance indices (Andersen, et al., 2017); and
- Adjusting the configuration to the diverse production scenario (Gadalla and Xue, 2017);

The issue of scaling capability is solved by increasing or reducing the quantity of RMTs in the manufacturing system which is parallel flow line (Benderbal, et al., 2017; Youssef, et al., 2006; Wang, et al., 2017; Dou, et al., 2009; Goyal, et al., 2013; Son, et al., 2001; Spicer, et al., 2002; Koren and Ulsoy, 2002; Attanaik, et al., 2010; Ai-Ping, et al., 2011). Further, Youssef and co-authors (Youssef, et al., 2007), recommended the utilization of multi-machine tool with higher system availability and less cost instead of increasing the machine tools. Further, the greater number of spindle heads the higher the capability of RMT becomes where the model proposed by Deif and co-authors (Deif, et al., 2006) and Spicer and co-authors (Spicer, et al., 2002) changes the capability by multi-spindle modules.

The issue of functionality is regarded to change the RMTs modules, where Shabaka and co-authors (Shabaka and ElMaraghy, 2007), generated the feasible configuration matched with the required functions according to the axes motion. Furthermore, Mpofu and co-authors (Mpofu, et al., 2008), used the Degree of Freedom to stands for the motion axes and described the manufacturing process in a clear way.

The issue of selection of the most satisfied configuration, the various performance parameters are used as goals to evaluate the configuration, such as the cost, availability, quality, and utilization (Mittal and Jain, 2014; Kuzgunkaya and ElMaraghy, 2007). As a support to reconfiguration between different configurations (Heisel and Meitzner, 2006) accounted for reconfiguration cost and RMT reconfigurability in the design process. Further, Kuzgunkaya and ElMaraghy (Kuzgunkaya and ElMaraghy, 2007) and Benderbal and co-authors (Benderbal, et al., 2017) takes the cost and reconfigurability as indices to manage the RMT location in system, while Goyal and co-authors (Goyal, et al., 2013), take the axes motion to determine the module assembly in the machine, and Gadalla and co-authors (Gadalla and Xue, 2017), takes consideration of configuration parameters and reconfiguration process. Ahuett and Molina (Ahuett and Molina, 2005) also identified upgradeability and adaptability as main indices for the modular configuration with the consideration of the RMT intended evolution process.

The issue of modeling the design process aimed at the reconfiguration and improving the effectiveness of the decision-making is addressed by Gadalla and Xue (Gadalla and Xue, 2017) who introduced a design approach for RMT configuration with consideration of configuration parameters and reconfiguration process, and Wang and Koren (Wang and Koren, 2012), mainly discussed the scalability planning for the reconfiguration. Benderbal and co-authors (Benderbal, et al., 2017) develop a multi-objective method to manage the machine location while minimizing the transition effort and maximize the responsiveness.

According to the literature review, Table 2.4, it is clear that the existing methods for RMT configuration design have some shortcomings, such as the lack of the multi-spindle configuration, the lack of the reconfiguration with the periodic perspective and the lack of the descriptive model. The following issues are identified:

- Describing the RMT configuration in a clear, dynamic and computational way;
- Generating the feasible configuration while considering the capability and functionality concurrently;
- Determining the most satisfied configuration by addressing the trade-off between cost and reconfigurability; and
- Enabling the design process to explore the solution for different scenarios.

# Table 2.4. Overview of Important Papers for Identifying the Research Motivation in Design of RMT Configuration

| Key Approaches for Reconfigurable Configuration Design | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Paper | Configuration Type | | | | Design Scenario | | | Design Decision (Output) | | | | | | Constraints | | Goals | | | | Research Gap |
| | Machine-Level | | System-Level | | | | | Machine-Configuration | | | System-Configuration | | | | | Min Cost | | Max Reconfigurability | | |
| | Single-Spindle Head | Multi-Spindle Head | Series-Line | Parallel-Line | Environmental Foundation[1] | Variance of Product Design | Fluctuation of Product Demands | Module Type | Module quantity | Assembly Relationship | Machine type | Machine quantity | Machine Position | Scaling the Capability | Converting the Function | Direct Cost | Extra Cost | Utilization of the existing resource | availability of the future reconfiguration | |
| Gadalla, et al., 2016 | √ | - | - | - | 1 | √ | - | - | √ | - | √ | - | - | - | √ | √ | √ | - | - | Limited to the several manufacturing function. Lack of models on the reconfigurability. Ignoring the design for changing demands. |
| Benderbal et al., 2017 | √ | - | √ | - | 0 | √ | - | - | - | - | - | √ | √ | - | √ | √ | - | √ | √ | Ignoring the implementation effort. Concentrating on the system layout. Ignoring the reusability of the existing resource. |
| Xu, et al., 2017 | √ | - | - | - | 1 | √ | - | √ | √ | √ | - | - | - | - | √ | - | - | √ | - | Lack of the cost analysis. Unable to satisfy the changing demands |
| Goyal, et al., 2012, 2013 | √ | - | √ | - | 0 | √ | √ | √ | √ | - | - | √ | - | √ | √ | √ | - | - | √ | Given configuration candidates. Lack of considering the extra cost.. Increasing the complexity with the large number of machines. |
| Mpofu, et al., 2008 | √ | - | - | - | 1 | √ | - | √ | √ | √ | - | - | - | - | √ | √ | - | √- | - | Unavailable for the large candidate library without the quantitive model. |
| Wang, et al., 2012 | - | - | - | √ | 1 | - | √ | - | - | - | √ | √ | √ | √ | √ | √ | - | √ | - | Lack of the research on the flexible reconfiguration for dynamic market. Limited to the functional conversion. Ignoring the operational cost. |
| Son, et al., 2010 | - | - | - | √ | 0 | - | √ | - | - | - | √ | √ | √ | √ | - | √ | √ | - | - | Lack of the reconfiguration perspective. |
| Pattanaik, et al., 2007 | - | √ | - | - | 1 | √ | √ | √ | √ | - | - | - | - | - | √ | √ | - | - | - | Lack of the specific analysis of capability and functionality requirement. |
| Dou, et al., 2009 | - | - | - | √ | 1 | - | √ | - | - | - | √ | √ | √ | - | √ | √ | - | √ | √ | Lack of details in RMT configuration |
| Abdi, et al., 2009 | √ | - | - | - | 0 | √ | √ | - | - | - | √ | - | - | √ | √ | √ | √ | √ | - | Lack of details in RMT configuration |
| Youssef, et al., 2008, 2007 | - | √ | - | √ | 0 | √ | - | √ | √ | √ | √ | √ | √ | √ | √ | √ | | | √ | Fixed configuration candidate. Lack of details in RMT configuration |
| Liu, et al., 2008 | √ | - | - | - | 0 | - | √ | √ | √ | - | - | - | - | - | √ | √ | √ | √ | - | Unable to satisfy the changing demands |
| Nan, et al., 2012 | √ | - | - | - | 0 | - | √ | - | - | - | √ | - | - | - | √ | √ | √ | - | - | Lack of the reconfigurability in design; Lack of considering the capability changes. |
| Ai-Ping, et al., 2011 | √ | - | - | - | 1 | - | √ | - | - | - | √ | - | - | - | √ | - | - | - | - | Unable to deal with a large number of candidates. Lack of considering the capability changes. |
| Chen, et al., 2005 | √ | - | - | - | 0 | - | √ | √ | √ | √ | - | - | - | - | √ | - | - | √ | √ | Unable to satisfying the changing demands Similarity Analysis is Fuzzy |
| Wang, et al., 2017 | √ | √ | - | - | **1** | √ | √ | √ | √ | √ | - | - | - | √ | √ | √ | √ | √ | √ | |
| 0 stands for the creating entirely new systems satisfying the requirements;<br>1 stands for the modifying the existing systems to fit the new requirements. | | | | | | | | | | | | | | | | | | | | |

The gaps identified in this section are further recognized as research opportunities, see Section 2.4.3, that are further addressed in this dissertation in Chapter 6, Section 6.1.

### 2.3.2. Reconfigurable Inspection System (RIS)

In the era of Industry 4.0, Cyber-Physical System (CPS) is defined as the integration of virtual and physical processes, where the readily available data-accessing and data-processing services via the Internet of Things (IoT) results in the interconnected system (Lee, et al., 2008). Growing use of sensors and communication network leads to the continuous data feedback. A Digital Twin and Digital Thread, a data-based virtual copy of an industrial entity is used to assess the current performance of a manufacturing system and modify the behaviors of the system based on the predicted future effects (Gabor, et al., 2016). In response to the digital manufacturing, CPS is expected to develop the data-oriented dynamic management of multiple-stage manufacturing process, where informed decision-making related to enhancing the efficiency of the manufacturing process is supported by knowledge excavated from raw data (Gabor, et al., 2016; Lee, et al., 2015). The dynamic management supports designers to upgrade system automatically via repeatedly identifying the errors and handling the errors in order to the sustainable development of manufacturing process.

In pace with the rapid development of information technology, the smart manufacturing needs to be equipped with the ability to automatically detect the current status of the manufacturing process. The process detection can ensure that the process errors are identified timely so that RMS can be reconfigured at the available point and reduce the poor-quality product (Kore, 2013). In the RMS, the Reconfigurable Inspection System (RIS), consisting of multiple RIMs, is used to achieve the detection of product quality (Koren, 2010). Meanwhile, the RIS is based on Stream of Variation (SoV) theory that provides an available way with the aid of RIS to diagnose the root cause of the error (Barhak, et al., 2005). Hence, the effective detection mainly relies on enough status data from RIS, and thereby the process errors of RMS are quickly identified.

The RIS configuration design can provide the customized detection ability with sensitive to the process error and collect enough data to support the identification of error root cause.

The gaps identified in this section are further recognized as research opportunities, see Section 2.4.3, that are further addressed in this dissertation in Chapter 6, Section 6.2.

### 2.3.3 Reconfigurable Manufacturing System (RMS)

In nowadays market environment manufacturing processes could be affected by external factors (product variances or demand fluctuations) or internal factors (random failures of equipment), which leads to the difference between the expected state and the real state (Bruccoleri, et al., 2006). Thus, managing and updating the system is a matter of great concern in the realization of efficient and stable production as a support to digitalized manufacturing. In order to do so, a manufacturing system should have reconfigurable characteristics. That is, the manufacturing system is required to combine the individual production with adaptive control, which comprehensively improves the manufacturing efficiency, enhances the production quality, and increase the responsiveness (Mehrabi, et al., 2000). The Reconfigurable Manufacturing System (RMS), can repeatedly realize the reconfiguration via changing the modular structure in order to adapt the dynamic requirement as proposed by Wang and co-authors (Wang, et al., 2017).

According to the basic properties of a complex system, the manufacturing system consists of multiple devices with different functions and configuration design, which includes solutions for the different granularity, such as the devices, cells, and systems. The solutions for the different granularity configuration design is related to the diverse constraints and goals, which causes a systemic exploration for design. Furthermore, compared with the traditional manufacturing systems, in the RMS the repeated co-design of the different granularity design is necessary, which increases the complexity in the design of its multi-granular configuration. In view of the interaction between different granularity configuration designs, there is a need for the construction of the design decision network for RMS configuration. Further, in order to maintain the dynamic management of the manufacturing process in RMS, the main problem is the systemic exploration of multiple- granularity configuration design. However, currently, researchers on RMS configuration design are mainly focused on single granularity design, resulting in the lack of research on comprehensive performance among the different granularity configuration designs. The challenge is addressed by integrating the decision-model for single-granularity configuration design and the interaction-model between multiple-granularity configurations.

The RMS configuration design is divided into module granularity, equipment granularity, and system granularity.

***A. Module Granularity Design (MGD).*** MGD refers to the configuration design on the minimum space-time dimension, such as the configuration design of an RMT or RIM. As the finest granularity, it is the foundation of system strategy exploration. The input to the MGD is the module library and operation requirements; the output is the configuration design of the device. The essence of the design process mainly revolves around operation requirements, adding, deleting, or moving modules to make the equipment configuration change.

***B. Device Granularity Design (DGD).*** DGD takes the equipment as the design unit, and its space-time scale is larger than the MGD. The input to the DGD is the equipment library and process requirements, and the output is the subsystem configuration design. The essence of the DGD mainly revolves around the process requirements, adding, deleting, or moving the equipment, resulting in changes in the configuration of the subsystem.

***C. System Granularity Design (SGD).*** SGD is the concurrent design of multiple subsystems, and it needs to be represented on a larger spatial scale. The SGD input is the subsystem configuration design (such as the production system, the control system, etc.) and the market demands. The output is the overall system configuration design. The SGD is based on the overall characteristics of the system as a whole, and the system is adjusted and integrated to achieve better resource allocation.

The RMS strategy provides the opportunity to explore satisfying solutions for the different granularity configuration design accounting for interactions between their design activities.

The gaps identified in this section, multiple-granularity configuration, are further recognized as research opportunities, see Section 2.4.3, that are further addressed in this dissertation in Chapter 6, Section 6.3.

## 2.4 Identifying Research Opportunities and Justification

In this chapter, methods, and approaches related to the design of engineering systems are considered. State of the art in design engineering systems, such as multistage manufacturing processes, from the aspect of adaptable and concurrent design, are presented in Section 2.1., system operability analysis in Section 2.2, and system reconfigurability is presented in Section 2.3.

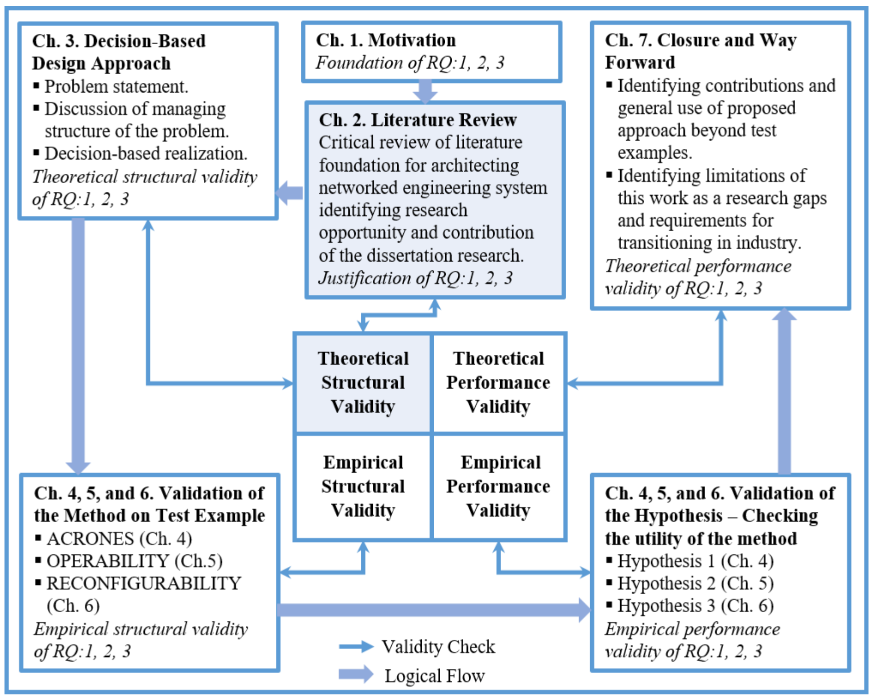


**Figure 2.1. Validation Square Roadmap**

Capabilities of methods and approaches in the design of multistage manufacturing processes are critically evaluated with respect to the needs of adaptable, operable, and reconfigurable design, introduced in Chapter 1, as a part of theoretical structural validation, Figure 2.1. Research opportunities are identified from these reviews and research questions and research hypothesis are justified from Section 1.4.2.

### 2.4.1 Research Opportunities in Dissertation

Research opportunities that are identified through critical literature evaluation are presented in this section, where a connection between identified research opportunities and research question, proposed in Chapter 1, Section 1.4.2, presented in Table 2.5.

*Adaptable Concurrent Design of Networked Engineering Systems*

***Concurrent Design of NES.*** It is evident through the critical literature review that the current approaches for designing NES are neither agile and usually do not have a high degree of tolerance for design attributes (tools and/or sensor) and errors (that are introduced and propagate) during the process. Methods and approaches in the design of NES, Section 2.1.1, where it can be seen that proposed methods are not considering the adaptable and concurrent design of NES. In a complex system design, such as the design of NES, there is a need to design a system to be diagnosable, controllable, and cost-effective, that will achieve certain product quality. Hence, concurrent observing of diagnosability, controllability, and cost-effectiveness with flexibility in selection and determination of design parameters in the design of NES is a research opportunity that is considered in this dissertation as part of the flexible design of NES, see Table 2.1.

***Managing Complexity in Design of NES.*** As discussed in Section 2.1.3, not all methods are applicable to the concurrent design of NES. Analytical target cascading (ATC), and advanced version of ATC, such as PATC, multi-objective optimization, a min-max multi-objective optimization, parent frontier, evolutionary algorithms, and many other methods that are encountered in this research, Table 2.1, are not useful in the concurrent design of NES. On the other side, the compromise DSP construct (Mistree, et al., 1993a) is applicable for concurrent design of NES, where Robust Concept Exploration

Method (Chen, 1995) is applicable for concurrent design of NES under uncertainty. Further, Augmented Lagrangian Coordination (ATC) (Allison and Papalambros, 2010) can be used from decomposition-based design side in clustering top-level model; afterwards, Multi-Objective Optimization (MOOP) (Narzisi, 2008) could be used, as well as Integer and Combinatorial Optimization (Wolsey, and Nemhauser, 2014) and partial use of Multistage Stochastic Programming (Defourny, 2012) for sequential decision making under uncertainty. Solving a multi-objective mathematical problem in the design of NES is a challenging task and it requires incorporations of several methods that are considered in this research.

***Extensive Solution Space Exploration***. As presented in Section 2.1.2, solution space search can be simulation-based, optimization-based, and knowledge-based. However, in the design of NES, there is a need for extensive solution space search that is simulation-based and atypical due to the fact that simulation-based exploration is used for fast not extensive search. Extensive solution space exploration is based on Design of Experiments (DOE) where results are located and analyzed as a cost-quality tradeoff. Extensive solution space search, locating and analyzing a range of solutions as the cost-quality tradeoff is considered in this dissertation.

***Robust Design of NES***. In the design of NES, from the aspect of a control system design, robust design is addressed where only noise and model parameters uncertainty is considered, Section 2.1.1. However, the robust design of NES is addressed where uncertainty in noise, model parameters, model structure, and propagated uncertainty is considered, Section 2.1.4. Furthermore, uncertainty is considered in the design of NES from the aspect of a mechanical system design, not in the concurrent design of NES.

Concurrent design of NES under all types of uncertainty is worthy of investigation and considered in this dissertation as part of the flexible design of NES.

*Operable Design of Networked Engineering Systems*

Operability is the bond between design and control that is established in the early 40s by Ziegler and Nichols (Ziegler and Nichols, 1943). More importantly, operability gives a unique opportunity to determine the functionality of the design. Different linear and non-linear operability methods are presented in Section 2.2. Nevertheless, these methods are well known in the literature and have found extensive use in the plant design. However, these methods are not suited for use in the design of NES, and only applicable if a design engineer has domain knowledge. Further, these methods are verified with a simple reacting system. For complex systems, such applications would require the solution of larger optimization problems and multivariable controllers.

**Table 2.5. Connection between Research Opportunities and Research Questions through Critical Literature Review**

| Research Opportunity | Critical Literature Review | Research Question |
|---|---|---|
| Adaptable Design<br>▪ Concurrent design<br>▪ Managing complexity<br>▪ Solution space exploration<br>▪ Robust design | Section 2.1 | Research Question 1<br>Chapter 1, Section 1.4.2 |
| Operable Design | Section 2.2 | Research Question 2<br>Chapter 1, Section 1.4.2 |
| Reconfigurable Design | Section 2.3 | Research Question 3<br>Chapter 1, Section 1.4.2 |

In this dissertation, it is recognized that there is a need to expand operability analysis to fit any engineering system rather than plant design while framing the operability and disturbance spaces without prior domain knowledge and analyzing system functionality with change in the requirements in addition to disturbances, see Table 2.5.

*Reconfigurable Design of Networked Engineering Systems*

In the fourth manufacturing revolution responsiveness and reconfigurability are important as discussed in Section 2.3. The speed at which a system can meet changing business goals and produce new product models refers to responsiveness. The ability of the manufacturing system to quickly launch new products on existing systems, and to react rapidly and cost-effectively to market changes, including changes in product demand refers to reconfigurability.

In this dissertation, it is recognized that most existing reconfigurability methods are limited to specific RMT paradigms and their respective module libraries. Further, there is a need to achieve the data-oriented detection of the product quality with the minimum but sufficient inspection machines, see Table 2.5

### 2.4.2 Potential Research Opportunities

The primary goal is to create a new knowledge, make a transformative influence in the design of networked engineering systems adaptable to ambitious market demands, and to accommodate the Industry 4.0 design principles based on the philosophy that design is fundamentally a decision making process. The principal motivation is to establish a computational framework that is suitable for the design of low cost and high-quality networked engineering systems adaptable to ambitious market demands in the context of Industry 4.0. Further, this dissertation is the foundation for the computational framework, Design for Dynamic Management, to transit in the industry where potential research gaps and research questions are identified that will be addressed in future work.

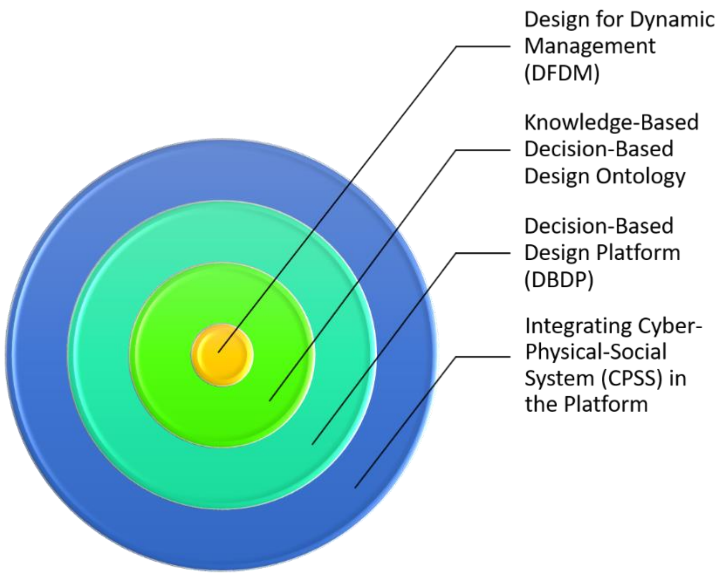


**Figure 2.2. Connection between Research Opportunities in Ph.D. Dissertation and Future Work**

Research opportunities identified in the dissertation are presented in this section, where the connection between research opportunities in the Ph.D. dissertation and future work are presented in Figure 2.2. Potential research opportunity in future work are:

***Potential Research Opportunity 1.*** *Knowledge-Based Decision-Based Design Ontology*. There is a value to learn how knowledge can be captured and reused in the design of networked, multidisciplinary engineering systems. The goal is creating the scientific and educational foundation for multidisciplinary knowledge exchange in the design of NESs that will transform the way systems, product-service system are designed and form a critical component of an enterprise's intellectual capital.

***Potential Research Opportunity 2.*** Defining decision support problem construct, decision template, and ontology in order to reach platformization as a support to digitalized manufacturing. The requirements for a platform to support human decision making and to transit in the industry are defined users template (creator, editor, and implementer), define a flowchart of decision-based design, and ensuring knowledge-based decision support.

***Potential Research Opportunity 3.*** *Integrating Cyber-Physical-Social System (CPSS) in the Platform.* Industrial social system and product/service system development where Cyber-Based Design (CBD) will be integrated with social networks. The requirement is to develop cyber-social design decision network that will accommodate social aspect.

## 2.5 Synopsis of Chapter 2

In this chapter, existing methods and approaches related to the design of networked engineering systems (NES) are critically reviewed. In Section 2.1, state of the art in the adaptable and concurrent design of NES is reviewed, while accounting for flexibility in design. It is established that main issues in adaptable design of NES are (1) concurrent design of mechanical and control system, (2) design a system to be diagnosable, controllable, and cost-effective, (3) managing high complexity of the mathematical models that represent NES, and (4) robust design of NES while accounting for different types of uncertainty. In Section 2.2, state of the art in system operability in the design of NES is reviewed. It is established that main issues in the operable design of NES are (1) existing methods are not suited for use in the design of NES, (2) require domain knowledge, and (3) not applicable for larger problems and multivariable controllers. In Section 2.3, state of the art in system reconfigurability in the design of NES is reviewed. It is established that main issues in the reconfigurable design of NES are (1) current methods are limited to specific RMT paradigms, and (2) need for data-oriented detection of the product quality with the minimum but sufficient inspection machines. Finally, in Section 2.4, gaps in the existing methods are identified and requirements for the design of NES are posted in order to justify the contributions of the research questions presented in Chapter 1. Further, potential research opportunities as the extension of current research opportunities are identified and will be further addressed in a future work.

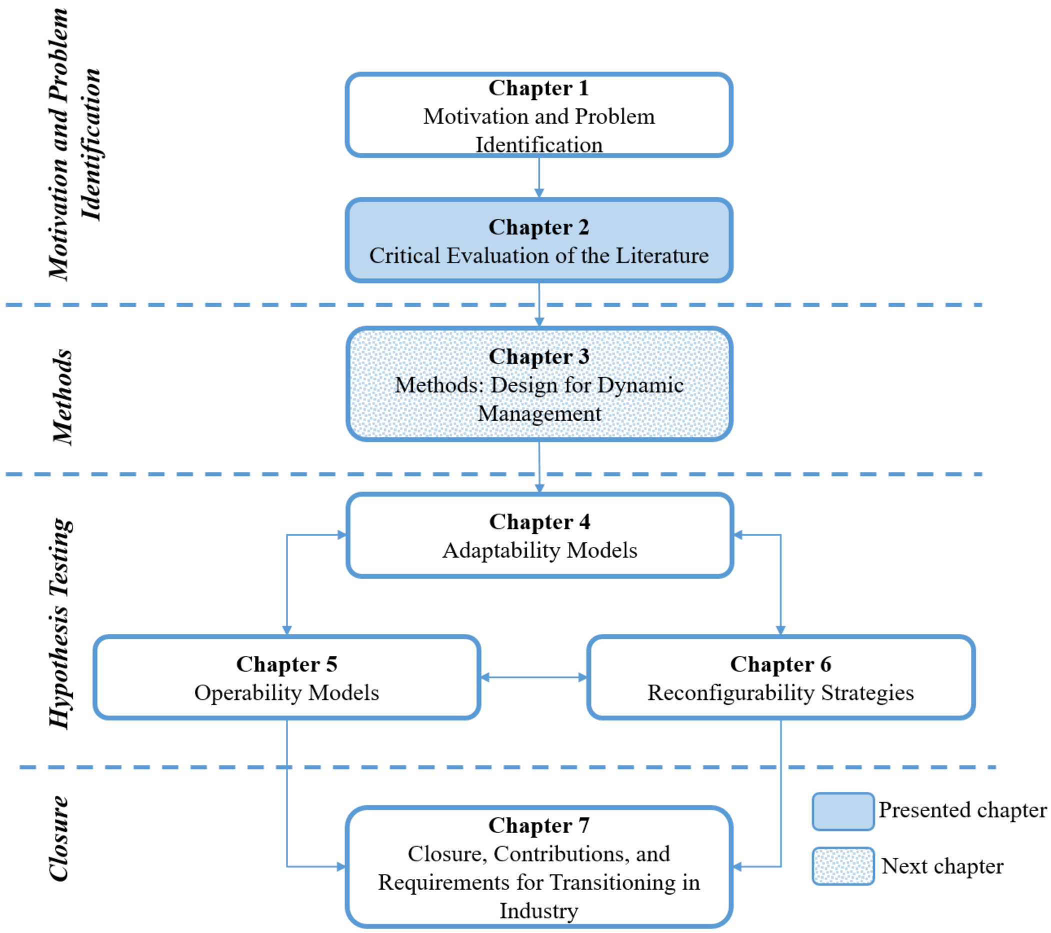


**Figure 2.3. Organization of the Dissertation – Presented and Next Chapter**

In Chapter 3, problem statement, research approach, and methods, followed by theoretical structural validity are considered, as presented in Figure 2.3. Problem statement followed by problem formulation are presented in Sections 3.1 and 3.2. Mathematical background of models that represent NES is presented in Section 3.3. A computational framework for decision-based design, *Design for Dynamic*

*Management,* is presented in Sections 3.4. Finally, in Section 3.5, the theoretical structural validity of the proposed approach is examined and verified.

# CHAPTER 3

# DECISION-BASED DESIGN OF NETWORKED ENGINEERING SYSTEMS

In this chapter, problem definition of the design of Networked Engineering Systems (NES) adaptable to dynamic changes, unexpected disturbances, and uncertainty that result with a low-cost process and high-quality product is introduced. Further, the research gaps, introduced and defined in the research questions presented in Chapter 1 and further justified through literature review in Chapter 2, are identified. Identified gaps lead to the primary research question that is worthy of investigation "*What is the computational framework that facilitates the decision-based design of networked engineering systems adaptable to ambitious market demands as a support to further digitization in the context of Industry 4.0*?". Mathematical formulation of the NES is considered as a background for Chapters 4 - 6, and decision-based design computational framework, *Design for Dynamic Management*, is introduced where adaptable design, operability analysis, and reconfiguration strategies are considered.

The problem definition, located gaps, and a detailed explanation of the examples are presented in Section 3.1. Further, the problem is formulated as the cDSP construct and presented in Section 3.2. In Section 3.3, mathematical background of the models (adaptability, operability, and reconfigurability) are presented. In Section 3.4, decision-based design computational framework, *Design for Dynamic Management,* is presented. Lastly, the theoretical structural validity of the proposed computational framework is discussed in Section 3.5.

## 3.1 Problem Definition

Dynamic changes in the market due to wide variations in customer needs lead to mass customization where enterprises have to be capable to adjust the manufacturing processes according to the wide variations of product design and substantial change of product scale. On the other hand, global competition requires enterprises not only to provide the cost-effective manufacturing processes but also to improve the quality of product and shorten time to market. Smart manufacturing is increasingly being adopted by companies to respond to these changes in the market. It is required to obtain flexible production, big data analysis in real time, and establish/maintain connectivity among elements in the system. These smart manufacturing systems must be adaptable to dynamic changes and respond to unexpected disturbances, and uncertainty and these are the challenges addressed in this dissertation.

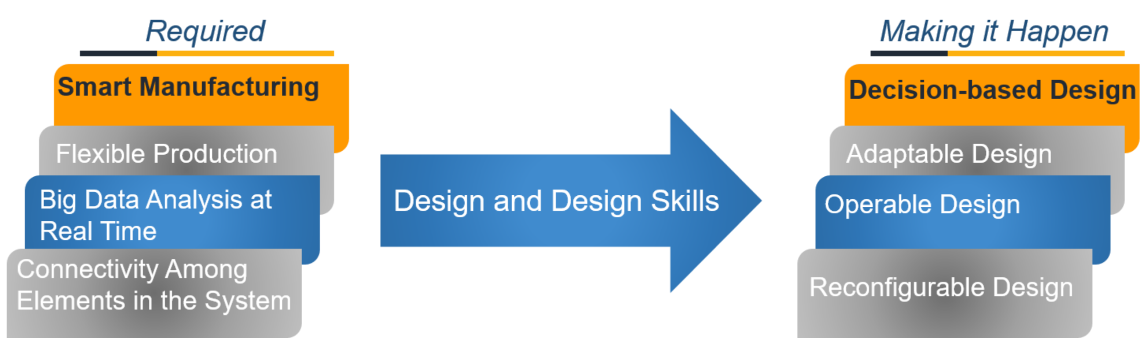


**Figure 3.1. Addressing Smart Manufacturing Features through Design for Dynamic Management**

In order to maintain the low-cost process and high quality of the product, there needs to design a system to be adaptable to dynamic and ambitious market demands. Hence, a decision-based design computational framework, Design for Dynamic Management (DFDM), is proposed as a support to adaptable, operable and rapidly configurable manufacturing processes, see Figure 3.1.

The key features of the computational framework are (1) flexible design through adaptability, see Section 3.4; (2) system design analysis at real time through operability, see Section 3.4; and (3) reestablishing connectivity among elements in the system through reconfigurability, see Section 3.4.

In this section, the problem is defined as a problem statement in Section 3.1.1, research gaps as motivation in Section 3.1.2, Test Problems 1 – 3 are explained in Section 3.1.3.

### 3.1.1 Problem Statement

The ***problem*** is to design a networked engineering system as a low-cost process that result with high-quality product adaptable to ambitious market demands in the context of Industry 4.0.

The ***challenges*** associated with the problem are (1) dynamic changes, (2) unexpected disturbances, (3) managing system complexity, (4) variation in product design, and (5) product scale change. In this dissertation first three challenges are addressed.

In the design of networked engineering system adaptable to dynamic market demands foundational requirements are identified in order to address prior mentioned challenges. These challenges are categorized into three groups.

***Requirement 1. Adaptable Design.***

- Flexibility in selection and determination of the values of design parameters without domain knowledge; and
- Concurrent design of a mechanical and control sub-systems.

***Requirement 2. Operable Design.***

- Determining regions of functional system design when requirements are changing; and
- Determining the dynamic performance of the system (stabilize and transit) in the presence of change.

***Requirement 3. Reconfigurable Design.***

- Strategy for reconfiguration of mechanical and control sub-systems in order to reestablish connection of elements in the manufacturing system.

### 3.1.2 Located Gaps - Motivation

After extensive search and literature review (over 250 publications) gaps are identified that ties to primary requirements presented in Section 3.1.1.

***Research Gap 1. Adaptability.*** Ties in Requirement 1. Through critical literature review, it is discovered that there is a need for adaptability in the design of networked engineering system. Adaptability is reflected in need for (1) extensive solution space exploration in order accommodate flexibility in selection and determination of the values of design parameters; (2) design without prior domain knowledge in order to accommodate dynamic market changes in requirements; (3) concurrent design of mechanical and control sub-system; and (4) include different types of uncertainty in order to explore robust solutions that will result with adaptable networked engineering system.

***Research Gap 2. Operability.*** Ties in Requirement 2. Through critical literature review, it is discovered that there is a need for operability in the design of networked engineering system. Operability is reflected in need for (1) analyzing system functionality at steady-state in order to determine system functionality in the presence of change; (2) analyzing system functionality at dynamic state in order to determine dynamic performance of the system in presence of change; and (3) overall system functionality with change in the requirements in addition to disturbances.

***Research Gap 3. Reconfigurability.*** Ties in Requirement 3. Through critical literature review, it is discovered that there is a need for reconfigurability in the design of networked engineering system. Reconfigurability is reflected in need for (1) strategy for reconfiguration of manufacturing tool; (2) strategy for reconfiguration of inspection tool; and (3) strategy for reconfiguration of a manufacturing system in order to remain competitive in global market.

Research Gaps 1 – 3 lead to the **primary research question** worth investigation "*In the context of Industry 4.0 what is the computational framework that facilitates the decision-based design of networked engineering systems adaptable to ambitious market demands as a support to further digitization?*"

### 3.1.3 Test Examples

In this dissertation, three different test examples are used to verify different components of the decision-based design computational framework presented in Section 3.4. Further, for adaptability a panel assembling process as a Test Example 1, for operability the continuous stirred tank reactors as a Test Example 2, and for reconfigurability a transmission box as a Test Example 3 is used.

***Test Example. Panel Assembling Process.*** Panel assembly represents an integral part of many manufacturing processes, one of those processes is the assembly of automobile bodies. Panel assembling process represents a simplification of auto body assembling process according to Apley and co-authors (Apley, et al., 1998), therefore, in this dissertation panel assembling is considered. Further, the assumption is that the panels substitute the auto body parts with 100% dimensional accuracy. The dimensional quality of the completed product is highly dependent on the level of accuracy with which the panels are tooled (fixtured). The issue of design and maintenance of accurate fixturing in assembling processes and dimensional quality of the workpieces is important and worthy of investigation.

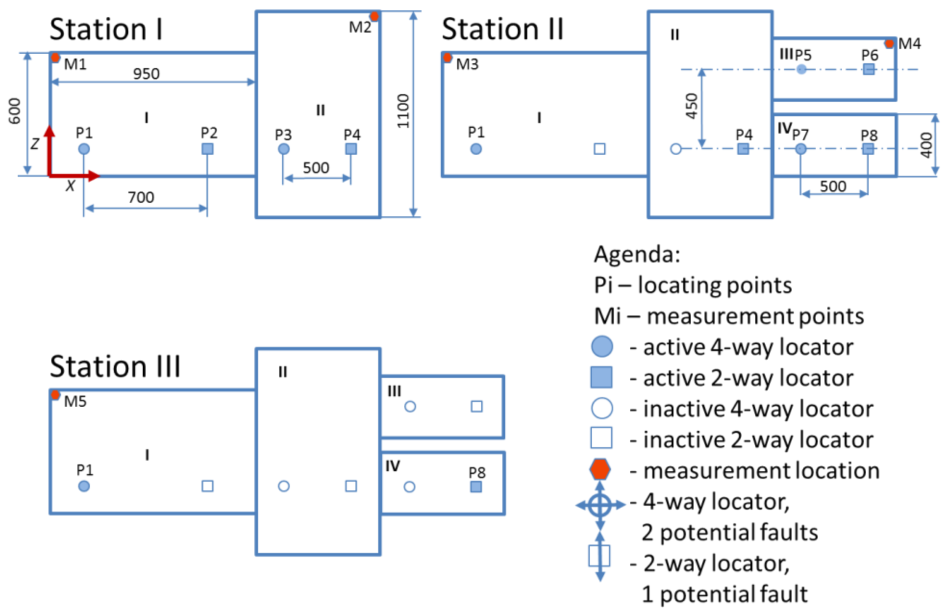


**Figure 3.2. Two-Dimensional Panel Assembling Process (Ding, et al., 2002)**

The common example for all models in this thesis is a two-dimensional panel assembly process, as presented in Figure 3.2, borrowed from Ding and co-authors (Ding, et al., 2002). As Ding and co-authors (Ding, et al., 2002) described in their work, there are three stations in the assembly process involved to assemble four parts (marked as I, II, III, IV in Figure 3.2) and examine the assembling process. Further, parts I and II are assembled at Station 1 (subassembly I + II) is assembled with parts III and IV at Station 2, and the final assembly with four parts are inspected at Station 3 for dimensional defects. Each part is restrained by a set of fixtures consisting of a four-way locator, which controls motion in both x- and z-directions, and a two-way locator, which controls motion only in the z-direction. A subassembly with several parts also needs a four-way locator and a two-way locator to completely control its degrees of freedom. The active locating points are marked as Pi, i = 1,..., 8, in Figure 3.2. In this example, N coordinate sensors are installed on all three stations. Each coordinate sensor measures the position of a part feature, such as a corner, in two orthogonal directions (x and z). The measurement points are marked as (Mi, i = 1,..., N) as shown in Figure 3.2.

***Test Example 2. Continuously Stirred Tank Reactors.*** The continuous stirred-tank reactor (cSTR) is a common ideal reactor type in chemical engineering. According to Schmidt (Schmidt, 1998), a cSTR is a model used to estimate the key unit operation variables when using a continuous agitated-tank reactor to reach a specified output. The mathematical model works for all fluids (liquids, gases, and slurries).

The behavior of a cSTR is approximated by a Continuous Ideally Stirred-Tank Reactor (cSTR) where perfect mixing is assumed by Schmidt (Schmidt, 1998). In a perfectly mixed reactor, the output composition is identical to the composition of the material inside the reactor, which is a function of residence time and rate of reaction. If the residence time is 5-10 times the mixing time, this approximation is valid for engineering purposes. The cSTR model is often used to simplify engineering calculations and can be used to describe research reactors. In practice, it can only be approached, in particular in industrial size reactors. cSTR's are known to be one of the systems which exhibit complex behavior such as steady-state multiplicity, limit cycles, and chaos.

Continuous flow stirred-tank reactors are usually applied in wastewater treatment processes. CSTRs facilitate rapid dilution rates which make them resistant to both high pH and low pH volatile fatty acid wastes. CSTRs are less efficient compared to other types of reactors as they require larger reactor volumes to achieve the same reaction rate as other reactor models such as Plug Flow Reactors Schmidt (Schmidt, 1998).

***Single and Two Continuously Stirred Tank Reactors.*** In this dissertation, the interaction between the design and control of single-CSTR and two-CSTRs-in-series systems with the first-order reaction of type A→ B is considered. The two configurations have the same feed flow rates and conversion specifications. Schematics of these systems are shown in Figure 3.3. For a liquid-phase exothermic reaction taking place in a jacketed cSTR the assumptions are that it has constant physical properties and complete mixing.

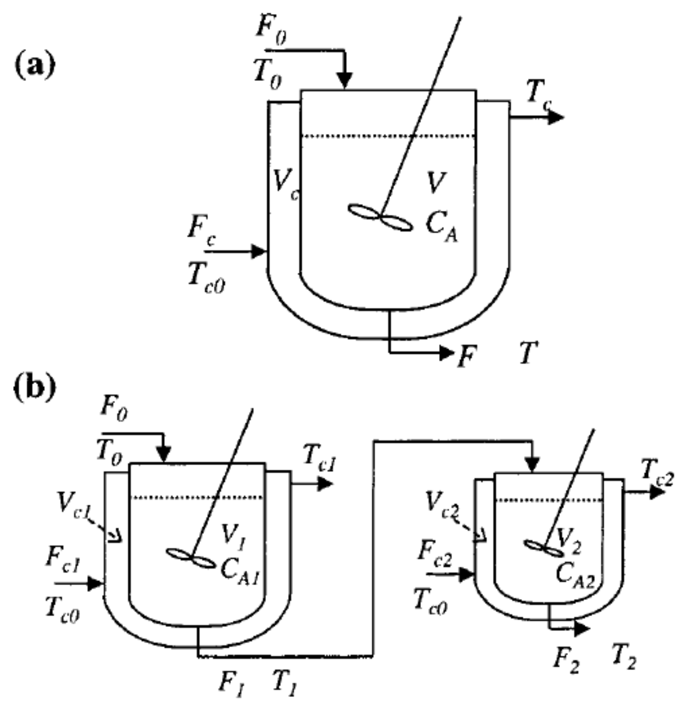


**Figure 3.3. Schematic of Single-CSTR and Two-CSTR in Series Systems (Subramanian, et al., 2001)**

***Test Example 3. Transmission Box.*** A transmission box, Figure 3.4, in a vehicle plays a supportive and connective role in the entire reducer assembly. The quality of the box directly affects not only the accuracy of the location of parts (e.g., shafts and gears) but also the life and performance of the reducer. This box is a typical box-type part and the main operations of manufacturing this part include a high-precision plane, bearing holes, screw holes, etc. Due to application demands in the field and an unstable demand/supply relationship, the multi-transmission boxes manufacturing process will face product variance or fluctuating order demand. A complex market environment forces the manufacturing system to be equipped with RMTs to have the ability to convert functionality and scaling the capability.

**Figure 3.4. Transmission Box for Vehicles**

In this dissertation, three design scenarios for transmission box production, Chapter 6, Section 6.5.1, are developed: (1) in the pre-planning phase, an RMT configuration is designed only around a given set of operational requirements; (2) the features of the operations change but the quantity remains the same; and (3) the quantity of the operations changes but the features remain the same.

## 3.2 Problem Formulation

In this section, the compromise Decision Support Problem (cDSP) construct is presented, see Section 3.2.1, a hybrid formulation for problem formulation and solution space exploration. In Section 3.2.2, the cDSP formulation for the design of the manufacturing process in N-station is presented.

### 3.2.1 The Compromise Decision Problem (cDSP) Construct

A Decision Support Problem (DSP) construct, proposed by Mistree and co-authors (Mistree, F., et al., 1993), based on the philosophy that design is fundamentally a decision making and model-based process which incorporates concepts from both traditional mathematical programming and goal programming, and makes new hybrid formulation.

***The Compromise Decision Problem (cDSP) Formulation.*** The word formulation of the cDSP construct supported by mathematical expressions is presented in this section and graphical representation in Figure 3.5.

---

**Given**

An alternative that is to be improved through modification.
Assumptions used to model the domain of interest.
The system parameters.
All other relevant information.

| | |
|---|---|
| $n$ | number of system variables |
| $p+q$ | number of system constraints |
| $p$ | equality constraints |
| $q$ | inequality constraints |
| $m$ | number of system goals |
| $g_i(X)$ | system constraint function<br>$g_i(X) = C_i(X) - D_i(X)$ |
| $f_k(d_i)$ | function of deviation variables to be minimized at priority level k for the preemptive case |
| $W_i$ | weight for the Archimedean case |

**Find**

The values of the independent *system variables* (they describe the physical attributes of an artifact).

$X_j$ $\qquad\qquad$ $j = 1,..., n$

The values of the *deviation variables* (they indicate the extent to which the goals are achieved).

$d_i^-, d_i^+$ $\qquad\qquad$ $i = 1,..., m$

**Satisfy**

The *system constraints* that must be satisfied for the solution to be feasible. There is no restriction placed on linearity or convexity.

$g_i(X) = 0;$ $\qquad i = 1,..., p$

$g_i(X) \geq 0;$ $\qquad i = p+1,...,p+q$

The *system goals* that must achieve a specified target value as far as possible. There is no restriction placed on linearity or convexity.

$A_i(X) + d_i^- - d_i^+ = G_i ;$ $\qquad i = 1,..., m$

The lower and upper *bounds* on the system.

$X_j^{min} \leq X_j \leq X_j^{max};$ $\qquad j = 1,..., n$

$d_i^- , d_i \geq 0$ and $d_i^- \cdot d_i^+ = 0$

**Minimize**

The *deviation function* which is a measure of the deviation of the system performance from that implied by the set of goals and their associated priority levels or relative weights:

Case a: Preemptive (lexicographic minimum)

$Z = [\ f_1( d_i^-, d_i^+), . . ,f_k( d_i^-, d_i^+)\ ]$

Case b: Archimedean

$Z = \sum_{i=1}^{m} W_i(d_i^- + d_i^+);$ $\qquad \sum W_i = 1;\ \ W_i \geq 0.$

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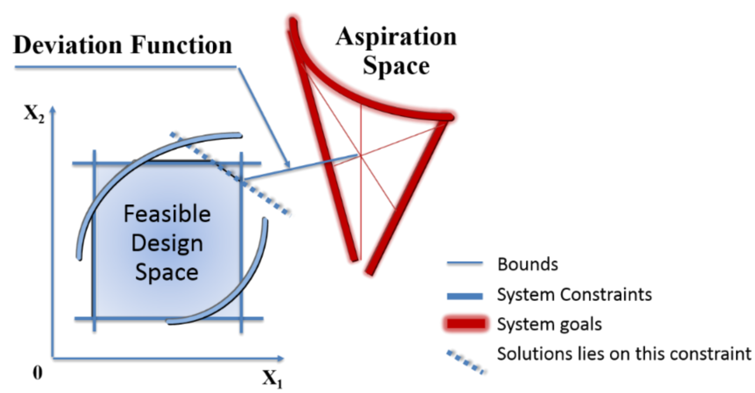



**Figure 3.5. The cDSP Model**

Solution space represents a feasible design space which is framed by system constraints and bounds, and aspiration space which is framed by designer wishes i.e. system goals. The deviation function represents the distance between the aspiration space (the 2D red bounded region in Figure 3.5) and a solution line (dash blue line in Figure 3.5) which is in the same time system a constraint line. Further, the solution line is not a single point solution but rather a range of solutions. The goal is to minimize the deviation function by minimizing the distance between aspiration space and solution space. For further information about system variables and deviation variables, system constraints and system goals, bounds and deviation function see Mistree and co-authors (Mistree, et al., 1993).

### 3.2.2 The Compromise Decision Problem (cDSP) Problem Formulation

The cDSP hybrid method is suitable for complex problems with multiple goals where goal functions are linear and/or non-linear, system variables are continuous, Booleans, linear and/or non-linear inequality constraints, equality constraints, and system boundaries. However, the cDSP computational environment known as DSIDES cannot precisely work with system variables that are integers. Therefore, in this dissertation, the cDSP construct is used due to its excellent features where the actual problem is partitioned and solved in MATLAB computational environment by use of different optimization techniques. The general cDSP formulation of the problem is presented further.

***Problem Statement.*** Problem statement is divided into three parts (1) determine the values of design parameters (tool and sensor attributes) that will give satisfying (robust) solutions regarding the process cost and quality of product; and (2) determine input ranges or design configuration that gives functional system design and satisfying dynamic performance of a system in the presence of change in requirements; and (3) determine reconfiguration strategy for mechanical sub-system (machine tool system) and control sub-system (inspection system) that gives flexible and functional system design while accounting for dynamic changes. Problem characteristics are: number of working stations is N, number of parts that goes in the assembling process is $n_p$, number of sensors in in the process is $M_{Pi}$, and number of tools in the process is $P_i$, and potential fixture failures in the process $m_r$. Problem requirements: process diagnosability, process controllability, process operability has to be full, and expected variations, $y_k$, have to be between -0.8 and 0.8 millimeters. Problem assumptions are: expected variations parameters follows Gaussian distribution with zero mean and known covariance. The overall objective is to minimize cost of the process and maximize quality of the product.

| | |
|---|---|
| **Given (Parameters)** | |
| Total number of operational stations | N |
| Number of stamping parts in the process | $n_p$ |
| Number and position of fixture points | $P_i$ [-]; (x, z) [mm] |
| Potential number of sensors and position | $M_{Pi}$ [-]; (x, z) [mm] |
| Dimensional quality (size of variations) boundary values are set | $Y_k$ [mm] |
| **Find (System Variables)** | |
| Total number of sensors and sensing stations | $M_{Pi,M}$; $M_{S,M\ (M=D,C,E)}$ |
| Use of PT`s control actions | PT |
| Sensing penalties | P |
| Sensors distribution schemes that are diagnosable, controllable, and cost-effective | $M_{i,k}$ |
| **Satisfy (Constraints)** | |
| Tooling constraints | Use of programmable tooling, see Equation 3.6 |
| Sensing constraints | Number, position and distribution of sensors, see Equation 3.6 |
| Process diagnosability | 100% or partial, see Equation 3.3 |
| Process controllability | 100% or partial, see Equation 3.5 |
| **Satisfy (Bounds)** | |
| Lower and upper number of sensors | $M_{Pi,M\ (M=D,C,E)}$, see Section 4.2 |
| Lower and upper number of sensing stations | $M_{S,M\ (M=D,C,E)}$, see Section 4.2 |
| Use of programmable tooling | PT, see Section 4.2 |
| Lower and upper limit of sensing penalties | P, see Section 4.2 |
| Deviation variables | $d_i^-, d_i^+ \geq 0$, see Section 4.2 |
| **Satisfy (Goals)** | |
| The mathematical foundations of goals Gi (i=1, 2, 3) in control theory are described in Section 3.3. | |
| Goal 1: Maximize process adaptability | Chapter 4, Section 4.2 |
| Goal 2: Maximize process operability | Chapter 5, Sections 5.1 and 5.2 |
| Goal 3: Maximize process reconfigurability | Chapter 6, Section 6.3. |
| **Minimize (Deviations)** | |

| | |
|---|---|
| Minimize deviation function | $Z = min \sum_{i=1}^{3}(W_i d_i^- + W_i d_i^+); \sum_{i=1}^{3} W_i = 1;\ W_i \geq 0;$ $d_i^-, d_i^+ \geq 0; d_i^+ \cdot d_i^- = 0\ \ (i = 1 - 3);$ see Section 3.2.1 |

## 3.3 Mathematical Background

In this section mathematical background of decision-based design computational framework, Design for Dynamic Management is presented. The dynamic management computational framework has three features, as presented in Section 3.1. The first feature is adaptable design through adaptability model, see Section 3.3.1, the second feature is system operability analysis through operability model, see Section 3.3.2, and the last feature is the reconfiguration of multiple elements in the system through reconfigurability model, see Section 3.3.3.

### 3.3.1 Adaptability Model

Adaptability model is a comprehensive mathematical model based on Stream of Variation (SoV) model. SoV model is used to simulate networked engineering system. Adaptability model is further partitioned due to its high computational complexity on process-decision models, such as diagnosability, controllability, and cost-effectiveness, and product-decision models, such as performance measurement model. Both process- and product-decision models are formulated as cDSP`s for effective solution space exploration.

***Stream of Variation Model.*** The problem that we are addressing in this dissertation is the design of a networked engineering system that will result in a low-cost process and high-quality product adaptable to ambitious market demands. It is a known fact that better a process is designed the better quality of the product will be. Operational tools, such as fixture locators in the assembling process, are managing dimensional accuracy of a product and are used on each station in the process. According to Jin and Shi (Jin, and Shi, 1999), for decades process performance is related to the product-inspection-oriented philosophy, where fixtures locators are not directly measured after being installed but the measurements were taken on the finished product. According to Jin and Shi (Jin, and Shi, 1999), the propagation of fixtures variation contributed from each station and its impact on the final product quality are described by the stream-of-variation model:

$$X_k = A_{k-1} \cdot X_{k-1} + B_k \cdot U_k + \xi_k \quad (3.1)$$

$$Y_k = C_k \cdot X_k + \eta_k \quad (3.2)$$

where

$X_k$ : part accumulated variation up to Station k including Station k,

$X_{k-1}$ : part accumulated variation up to Station k-1 including Station k-1,

$U_k$ : control vector at Station k, which is defined as the fixture error vector for both subassembly parts at Station k,

$Y_k$ : measurement obtained on Station k,

$\xi_k$ : noise due to unmolded effects, independent from other noise,

$\eta_k$ : sensor noise, independent from other noise,

$A_{k-1}$ : dynamic matrix, characterizes variation change due to part transfer from Station k to/and Station k+1,

$B_k$ : input matrix, determines how fixture variation affects part variation at Station k, and

$C_k$ : sensor locations information on a station.

Equation 3.1, is the state equation, which implies that part variation on Station k is influenced by two sources (1) the accumulated variation up to Station k-1, and (2) the variation on Station k. The Equation 3.2, is the observation equation. For further information about the system matrices see Jin and Shi (Jin, and Shi, 1999).

The SoV model is primarily developed for multistage assembly and machining processes. The diagram of SoV in an MMP for an N-stations assembling process, Figure 1.13. Further, the SoV model integrates the process and/or product design and quality information. Diagnosability, controllability, cost-effectiveness, and performance measurement are based on SoV model.

***Diagnosability.*** Diagnosability is the ability to detect faults and identify their cause, according to the control theory Ding and co-authors (Ding, et al., 2002). Diagnosability criteria is based on dimensional Stream of Variations (SoV) model, see Equations 3.1 and 3.2. The state-space formulation, Equations 3.1 and 3.2, are used to calculate the diagnosability matrix ($D_N$) Ding and co-authors (Ding, et al., 2002). The diagnosability index in design of NES is defined as:

$$\mu = \frac{\rho(D_N)}{\sum_{k=1}^{N} m_k} \tag{3.3}$$

where

$D_N$ : diagnosability matrix,

$\rho(\cdot)$ : rank of a matrix, and

$m_k$ : number of potential fixture faults at Station k.

Diagnosability index is between [0, 1], where 1 means that the process is completely diagnosable. The process diagnosability index Ding and co-authors (Ding, et al., 2002) is diagnosability criteria used in the design of NES.

***Controllability.*** Controllability is the ability to mitigate the errors and drive the system from an arbitrary state to a desired state along specified state trajectories Mantripragada and co-authors (Mantripragada, et al., 1999). Controllability criteria is connected with output controllability Mantripragada and Whitney (Mantripragada and Whitney, 1999):

$$U_k = T_k \cdot \bar{u}_k \tag{3.4}$$

where

$\bar{u}_k$ : vector of input parameters at Station k, and

$T_k$ : realizability matrix.

The term realizability is a property of the control vector $U_k$ signifying that there are solutions that will control the degrees of freedom of the workpiece Mantripragada and Whitney (Mantripragada and Whitney, 1999). Realizability matrix is further transformed into the controllability matrix Mantripragada and Whitney (Mantripragada and Whitney, 1999) that is used in this paper as the process controllability index:

$$\mu_C = \frac{C_k}{Y_k} \tag{3.5}$$

where

$C_k$ : controllability matrix, and

$Y_k$ : measurement obtained at Station k.

The controllability index is between [0, 1], where 1 means that the process is completely controllable.

***Cost-effectiveness.*** Cost-effectiveness is associated with sensing cost. Sensing cost is the expense of building sensing stations, using PT control actions, and penalties for reducing the number of sensing stations. The main assumption is that all parts assembled at any station can be physically obtained by sensors at a downstream station for their positional and orientation measurements. There are two ways of measuring product features during production (1) directly where sensors are installed directly on the assembly station and measurements are taken after the assembly operation is completed, and (2) indirectly where sensors are installed on dedicated stations and workpieces are transferred to a dedicated and measurements are taken. Stations with installed sensors are called sensing stations.

In this dissertation, cost-effectiveness is formulated as a goal function given the constraints of process diagnosability and controllability, as presented in Equation 3.6.

$$Cost = \min_{D,C}\left\{\mathrm{c}_1 \cdot \sum_{\mathrm{i}=1}^{\mathrm{N}} M_{Pi} + \mathrm{c}_2 \cdot \mathrm{M}_s + \mathrm{c}_3 \cdot \mathrm{PT} + \mathrm{c}_4 \cdot \mathrm{P}\right\} \quad (3.6)$$

where

$c_1$ : monetary cost of total number of sensors,

$c_2$ : monetary cost of sensing station,

$c_3$ : monetary cost for using PT control actions, and

$c_4$ : monetary cost for reducing the number of sensing station.

***Performance Measurement.*** The networked engineering system, such as MMP, is modeled as a discrete time linear dynamic system. In this dissertation, the main focus is on satisfying the dimensional quality of the workpiece through minimum control actions. Hence, dimensional quality is measured through the performance measurement that is formulated as a minimum effort problem. In order to control the assembling process, we are using a combination of feedforward control (FWC) and programmable tooling (PT). This combination of FWC and PT is a method for minimizing product variation in MMP. Feedforward control allows minimization of variations on a part-by-part basis using PT. The design of a control system includes variations estimation, modeling and analysis of variation propagation, and process/parts constraints, therefore, a control law is obtained using constrained optimization, see Milisavljevic (Milisavljevic, 2015).

Performance measurement model is presented as a constrained optimization problem where expected variations are minimized regarding estimated control actions, as presented in Equation 3.7.

$$PM = \min_{s_k} \sum_{k=1}^{N} [\bar{y}_k^T \cdot Q_k \cdot \bar{y}_k] \tag{3.7}$$

where

$s_k$ : estimated control actions, and

$Q_k$ : weighting coefficient matrix, shows differences in the importance and characteristics of the measured points.

### 3.3.2 Operability Model

In this section a steady-state operability index is introduced in order to determine is the input ranges are sufficient to achieve the desired output ranges in the presence of the expected disturbances. However, for well-designed system steady-state operability is not sufficient requirement, therefore, dynamic operability is introduced. Dynamic operability index is introduced to find the minimum time within which the process can respond to a disturbance or move to a new operating point with the available ranges of inputs. Hence, dynamic operability characterizes the inherent operability characteristics of the process. Steady-state operability and dynamic operability gives us information whether the whole system needs to be altered as no other controller will be able to improve the operability. This approach addresses both the servo and regulatory issues over the entire operating space of interest.

***Steady-State Operability.*** The definition of operability given by Vinson (Vinson, 2001) "A process is operable if the available set of inputs is capable of satisfying the desired steady state and dynamic performance requirements defined at the design stage, in the presence of the set of anticipated disturbances, without violating any process constraints", see Georgakis and co-authors (Georgakis, et al., 2003).

Process models are usually given in state-space representation:

$$\dot{x} = f(x, u, d) \tag{3.8}$$

$$y = g(x, u, d) \tag{3.9}$$

$$h_1(\dot{x}, x, y, \dot{u}, u, d) = 0 \tag{3.10}$$

$$h_1(\dot{x}, x, y, \dot{u}, u, d) = 0 \tag{3.11}$$

where

$x \in \mathbb{R}^{n_x}$ : state vector

$u \in \mathbb{R}^{n_u}$ : input/control vector,

$d \in \mathbb{R}^{n_d}$ : disturbance vector,

$y \in \mathbb{R}^{n_y}$ : output vector of the process,

$\dot{x}$ : time derivative of the state vector,

$\dot{u}$ : time derivative of the input/control vector,

$f: \mathbb{R}^{n_x+n_u+n_d}$ : nonlinear function, and

$g: \mathbb{R}^{n_x+n_u+n_d} \rightarrow \mathbb{R}^{n_y}$ : nonlinear function.

Constraints in the Equations 3.10 and 3.11 represent the process, product, and safety specifications, and the bounds on the magnitudes and the rate-of-change of the inputs. Further, these constraints are applied to the complete time history of the process and/or a certain time of the process.

In general, based on operational requirements, process outputs can be classified into two broad categories: (1) set-point controlled - outputs to be controlled at a desired value, and (2) set-interval controlled - outputs to be controlled within the desired range, see Georgakis and co-authors (Georgakis, et al., 2003).

Operability index (OI) is defined by different operating spaces, see Vinson and Georgakis (Vinson and Georgakis, 1998 and 2000). We will consider next operability spaces:

- Available Input Space (AIS) – inputs of the process able to change over a certain range;
- Achievable Output Space (AOS) – the collection of output points achieved by solving the model for the entire AIS;
- Desired Output Space (DOS) – desired operating window for the process outputs;
- Desired Input Space (DIS) – the set of input values required to reach the entire DOS.

Achievable Output Space (AOS) is a function of *u* and *d*, $AOS_u(d^N)$ where AOS is calculated by considering all the points inside the AIS, denoted by the subscript *u*, when the disturbances are at their nominal values, $d^N$. Desired Input Space (DIS) is a function of y and d, $DIS_y(d^N)$ where DIS is calculated by considering all the points inside the DOS.

Once we have outlined all required spaces we can define the Servo Operability Index in the Output Space (SOIOS) as:

$$SOIOS = \frac{\mu[AOS_u(d^N) \cap DOS]}{\mu[DOS]} \tag{3.12}$$

where

$\mu$ : measure function for calculating the size of the corresponding space.

The SOIOS indicates how much of DOS region is achieved with AIS. The value of the SOIS is between 0 and 1, where values bellow 1 implies that designer expectations are greater than designed process can deliver. Further, the SOIOS is useful in analyzing the operability of the existing plant designs, see Georgakis and co-authors (Georgakis, et al., 2003).

In nonlinear systems the boundaries of a given input space do not necessarily map to the boundaries of the output region. Behavior of nonlinear systems was exhibited by a vinyl acetate reactor studied by Subramanian and Georgakis (Subramanian and Georgakis, 2001).

New index is defined for new plant design or redesign of the existing plant, a Servo Operability Index in the Input Space (SOIIS) as:

$$SOIIS = \frac{\mu\left[AIS \cap DIS_y(d^N)\right]}{\mu\left[DIS_y(d^N)\right]} \tag{3.13}$$

The SOIIS indicates how much of the DIS is covered by AIS. The value of the SOIIS is between 0 and 1, where values below 1 indicates a need to increase the available ranges of some of the inputs, see Georgakis and co-authors (Georgakis, et al., 2003).

For linear systems the SOIOS and the SOIIS are giving us the same values. However, for nonlinear systems this is not the case.

In order to determine the regulatory operability of the process we need to determine the anticipated ranges of disturbances we need to define the Expected Disturbance Space (EDS). In steady state operability the EDS reflects on uncertainties in model parameters (heat of reaction, heat-transfer coefficients, kinetic constants, pressure, etc.), see Georgakis and co-authors (Georgakis, et al., 2003). The Regulatory Operability Index (ROI) is calculated as:

$$ROI = \frac{\mu[AIS \cap DIS_d(y^N)]}{\mu[DIS_d(y^N)]} \tag{3.14}$$

However, the ROI can be calculated based on the region of disturbances that can be tolerated with the available inputs, keeping the plant at the nominal operating point, see Georgakis and co-authors (Georgakis, et al., 2003). This is defined as Tolerable Disturbance Space (TDS). The ROI for TDS is calculated as:

$$ROI = \frac{\mu[TDS \cap EDS]}{\mu[EDS]} \tag{3.15}$$

Typically, others objective is to reject the expected disturbances, and, at the same time, be able to reach all the points in the DOS. Hence, the objective is to design a system that is insensitive to the expected disturbances, and, at the same time, be able to reach all the points in the DOS.

The overall operability of the process, i.e. the Operability Index (OI) is defined as:

$$OI = \frac{\mu[AIS \cap DIS]}{\mu[DIS]} \tag{3.16}$$

where DIS is the total Desired Input Space defined as the union of $DIS_d(y)$ for all $y$ in DOS, or the union of $DIS_y(d)$ for all $d$ in EDS.

$$DIS = \bigcup_{y \in DOS} DIS_d(y) = \bigcup_{d \in EDS} DIS_y(d) \tag{3.17}$$

The OI values are between 0 and 1, where values bellow 1 implies that designed process is not operable.

***Dynamic Operability.*** Dynamic operability is used to quantify the inherent properties of the process, see Uztiirk and Georgakis (Uztiirk and Georgakis, 2001). Dynamic operability measure is defined as "*The shortest time it would take a system to settle to the desired set point after a set-point change and/or a disturbance occurrence*", see Georgakis and co-authors (Georgakis, et al., 2003).

The operability measure is based on the idea that the time spent away from the desired set point is linked to potential losses due to off-specification products. Different types of feedback controllers can be utilized to evaluate this operability measure. However, a performance measure independent of the feedback controller to be used and capable of assessing the inherent limitations of the process is desirable. Minimum-time optimal controller suits these demands very well, see Georgakis and co-authors (Georgakis, et al., 2003).

Minimum-time optimal control problem for continuous systems is as follows:

$$t_f^*(y_{sp}, d) = \min_u \int_0^{t_f} dt$$
$$\text{s.t. } \mathcal{M}(x_0, u_0, y_{sp}, d \text{ given}) \tag{3.18}$$

where

$t_f^*(y_{sp}, d)$ : minimum time necessary to respond to a change in the set-point, $y_{sp}$, and to a disturbance $d$, and

$\mathcal{M}$ : include the final-time constraints.

Dynamic operating spaces are the extension of the operating spaces used in the steady-state operability to the dynamic problem. We will consider next operability spaces:

- Dynamic Available Input Space (DAIS) – set of input variables (constraints on the magnitudes, and the rate-of-change of the input variables;
- Dynamic Desired Operating Space (DDOS) – space formed by the combination of the DOS, EDS, and desired response times. The DDOS is defined as follows:

$$\text{DDOS} = \{(t_f, y_{sp}, d) | t_f \le t_f^d(y_{sp}, d), \forall y_{sp} \in DOS, \forall d \in EDS\} \tag{3.19}$$

where

$t_f^d(y_{sp}, d)$ : desired dynamic performance, or the maximum allowable response time, in tracking a set-point change, $y_{sp}$, in DOS and/or recovering from disturbance, $d$, in EDS.

- Dynamic Achievable Operating Space (DAOS) – operating space that represents the dynamic performance for a given choice of the DAIS, DOS, and EDS. The DAOS is defined as follows:

$$\text{DAOS} = \{(t_f, y_{sp}, d) | t_f \le t_f^*(y_{sp}, d), \forall y_{sp} \in DOS, \forall d \in EDS, u \in dAIS\} \tag{3.20}$$

Dynamic operability index (DOI) is defined as: "*the fraction of the operating ranges that can be achieved within the desired response time* $t_f^d(y_{sp}, d)$*given the available input ranges in DAIS*", see Georgakis and co-authors (Georgakis, et al., 2003).

Two additional spaces are introduced in order to mathematically define DOI. First operating space, $S_1$, is the space obtained by the combination of the set points in DOS and disturbances in EDS:

$$S_1 = \{(y_{sp}, d) | \forall y_{sp} \in DOS, \forall d \in EDS\} \quad (3.21)$$

Second operating space, $S_2$, is the space obtained by projecting the intersection of DDOS and DAOS onto $S_1$, and it represents the ranges of set points and disturbances within $t_f^d(y_{sp}, d)$:

$$S_2 = \{(y_{sp}, d) | t_f \leq t_f^d(y_{sp}, d), \forall y_{sp} \in DOS, \forall d \in EDS\} \quad (3.22)$$

DOI values are between 0 and 1, where 0 means worst performance and 1 means best performance. Mathematical representation of DOI is as follows:

$$DOI = \frac{\mu(S_2)}{\mu(S_1)} \quad (3.23)$$

where

$\mu$ : function for calculating the size of the corresponding space.

### 3.3.3 Reconfigurability Model

In this dissertation, we advocate in order to reconfigure manufacturing system there is a need to reconfigure both production line (reconfiguration of the machine tool) and the inspection system. Hence, the reconfigurability model has two sub-models (1) reconfiguration of machine tool model and (2) reconfiguration of the inspection system.

***Reconfigurable Machine Tool (RMT).*** The foundation of the reconfigurable machine tool (RMT) is a configuration tree. The mathematical model of the configuration tree as follows:

$$CT = \{u, v | u \in U, v \in V\} \tag{3.24}$$

where

| | |
|---|---|
| $CT$ | : configuration tree, |
| $u$ | : nodes, |
| $v$ | : edges, |
| $U$ | : node set of the RMT configuration tree, and |
| $V$ | : edge set of the RMT configuration tree. |

The definition of the node set *U* is:

$$U = \left\{u_{ijk} | i \in (1, \cdots, 7), j \in N, k \in 0, 1\right\} \tag{3.25}$$

where

| | |
|---|---|
| $u_{ijk}$ | : element in the node set *U*, |
| $i$ | : type of a node, see Table3.1, |
| $j$ | : identifier of the node of the same type, and |
| $k$ | : section of the configuration tree to which the node belongs. |

If *k*=0, the node belongs to the tool-side branch and if *k*=1, the node belongs to the workpiece-side branch. The example for a configuration tree to describe RMT configuration is presented in Figure 3.6.

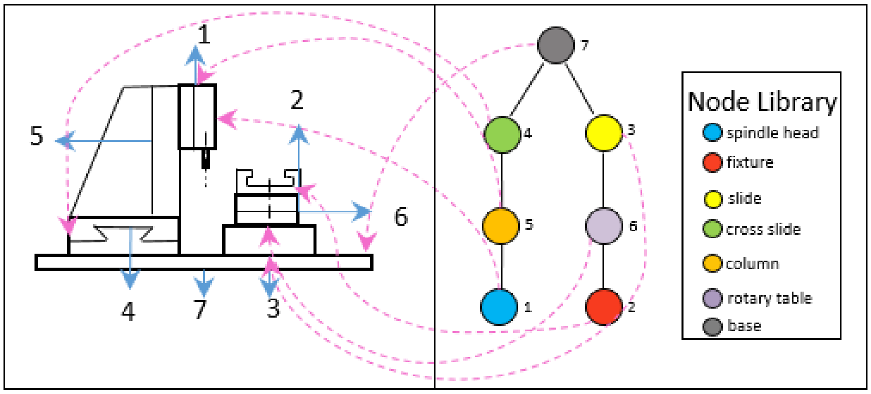



**Figure 3.6. Example of Mapping from Configuration to Configuration Tree**

In addition to the node set, the edge set is important. An edge consists of two nodes in an ordered pair. Every node in the configuration tree can be described by Equation (3.2). Thus, the edge set *V* is expressed as follows:

$$V = \{v = \langle u_{ijk}, u_{\grave{i}\grave{j}\grave{k}} \rangle | f_1(v) = 1, \langle u_{ijk}, u_{\grave{i}\grave{j}\grave{k}} \rangle \in U, i \neq \grave{i}\} \tag{3.26}$$

$$f_1(\langle u_{ijk}, u_{\grave{i}\grave{j}\grave{k}} \rangle) = \begin{cases} 1 & existing\ edge\ of\ u_{ijk}\ and\ u_{\grave{i}\grave{j}\grave{k}} \\ 0 & unexisting\ edge\ of\ u_{ijk}\ and\ u_{\grave{i}\grave{j}\grave{k}} \end{cases} \tag{3.27}$$

where

$v$ : ordered pair which specifies one edge in the configuration tree,

$u_{ijk}$ : parent node in the edge,

$u_{\grave{i}\grave{j}\grave{k}}$ : child node, and

$f_1$ : discriminant function of the edge.

**Table 3.1. Variable *i* and Corresponding Node Type**

| *i* | $u_{ijk}$ | Node type |
|---|---|---|
| 1 | $u_{1jk}$ | Spindle Head |
| 2 | $u_{2jk}$ | Fixture |
| 3 | $u_{3jk}$ | Slide |
| 4 | $u_{4jk}$ | Cross-Slide |
| 5 | $u_{5jk}$ | Column |
| 6 | $u_{6jk}$ | Rotary table |
| 7 | $u_{7jk}$ | Base |

If the function $f_1$ equals to 1 the edge between $u_{ijk}$ and $u_{i'j'k'}$ exists in the configuration tree. On the other hand, if the function $f_1$ equal to 0 there is no edge between $u_{ijk}$ and $u_{i'j'kp.}$ In order to ensure manufacturing stability, the following rules for the assembly relationship among modules are created:

***Rule 1.*** The modules for the same motion are always installed on different branches and there is no assembly relationship among the modules on different branches. The mathematical expression that supports this rule is:

$$\langle u_{ijk}, u_{i`j`k`} \rangle = 0$$
$$\sum_{k \neq k`} \sum_{i`} \sum_{j`} \langle u_{ijk}, u_{i`j`k`} \rangle = 0 \quad (3.28)$$

***Rule 2.*** There is at most one assembly relationship between any two modules. The module cannot be assembled with itself. This rule is expressed with the following equation:

$$\sum_{j} \langle u_{ijk}, u_{i`j`k`} \rangle = 0$$
$$\forall i \neq i` \sum_{j`} \langle u_{ijk}, u_{i`j`k`} \rangle \leq 1 \quad (3.29)$$

***Rule 3.*** The module with the tools and the module for the workpiece are always installed on different branches. This rule is expressed with the following equation:

$$\langle u_{1jk}, u_{2j`k} \rangle \; and \; \langle u_{2jk}, u_{1j`k} \rangle = 0 \quad (3.30)$$

***Rule 4.*** A module for rotary motion is always installed on a module for linear motion. This rule is expressed with the following equation:

$$\langle u_{6jk}, u_{3j`k} \rangle, \langle u_{6jk}, u_{4j`k} \rangle \; and \; \langle u_{6jk}, u_{5j`k} \rangle = 0 \quad (3.31)$$

***Rule 5.*** For linear motion, a module for up and down motion is always installed on a module for forward and back motion, while the module for forward and back motion is always installed on a module for left and right motion. This rule is expressed with the following equation:

$$\langle u_{4jk}, u_{3j^{`}k}\rangle, \langle u_{5jk}, u_{4j^{`}k}\rangle \; and \; \langle u_{5jk}, u_{3j^{`}k}\rangle = 0 \quad (3.32)$$

***Reconfigurable Inspection System (RIS).*** Typically in the manufacturing system, the inspectional station is usually set at the end of the line which is a cost-effective and popular in the industry. However, only part of errors can be detected, while the errors already caused some quality damage due to delayed detection. On the other hand, in saturated detection, each operational station is followed by an inspectional station, which can achieve the complete insurance of product quality but it is very costly and not necessary. Hence, the selection of a minimal but sufficient number of inspection stations to detect errors in the manufacturing process is needed. This can be accomplished by a reconfigurable inspection system (RIS) where solutions are located as a trade-off between cost and diagnosability within the RMS manufacturing process. As indicated earlier in Section 3.3.1 diagnosability is based on the SoV model. Accumulation and propagation of errors in the production process are modeled by the SoV model. Therefore, the identified root causes of errors via SoV model benefits the RIS configuration design in order to chieve the needed error diagnosis. The RMS detection process as a combination of RIS and SoV is presented in Figure 3.7.

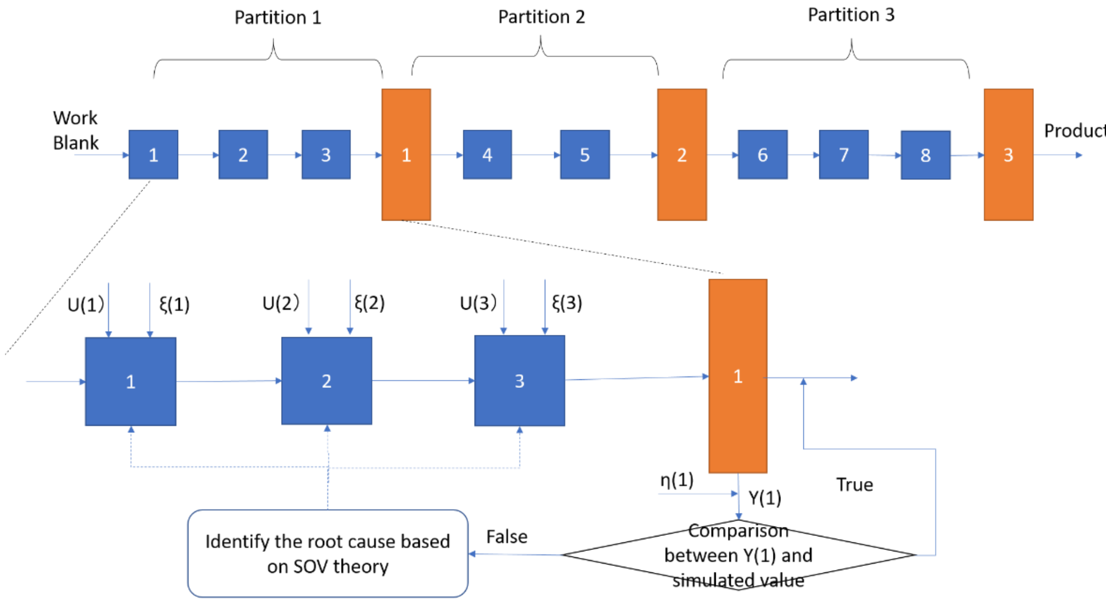



**Figure 3.7. Detection Mechanism via Integration of RIS and SoV**

The essence of identifying root cause via SoV model, see Equations 3.1 and 3.2, is to simulate the manufacturing process. The product quality error refers to the deviation of the actual position and the ideal position, and the main error sources generally include fixturing error caused by the imperfection of locators, datum error caused by the error of datum feature, machine tool error caused by a structural loop of the machine. The fixture error and the machine tool error belong to the current station, while the datum error is influenced by other station. Therefore, the virtual station is simulated by the data of datum measurement. If the virtual station has the same state with the corresponding real station, the real station is in a good quality, else, the station should be maintained or updated.

## 3.4 Design for Dynamic Management

In the context of Industry 4.0, a decision-based design computational framework, *Design for Dynamic Management*, as a support to adaptable, operable, and reconfigurable design of networked engineering system is proposed. The key features of the computational framework, see Figure 1.12, are:

i. Adaptability in Design of NES – inserting flexibility in selection and determination of design parameters where (robust) solution space exploration is taking place with *Adaptable Concurrent Realization of Networked Engineering Systems* (ACRONES) method. The ACRONES is a subset of *Design for Dynamic Management*, see the Quadrant 1 in Figure 1.12. Two models are developed to support adaptability in the design of NES. First, Adaptability Model for solution space exploration, see Chapter 4. Second, Adaptability Model under Uncertainty for robust solution space exploration, see Chapter 4.

ii. Operability in the design of networked engineering system is based on operability analysis Fisher and co-authors (Fisher, et al., 1988), Subramanian and co-authors (Subramanian, et al., 2001), cDSP construct, and minimum-time control Subramanian and co-authors (Subramanian, et al., 2001). Operability in design analyzes systems functionality with change in the requirements, see Quadrants 2 and 3 in Figure 1.12, and the dynamic performance of the system with a change in requirements. Two models are developed to support operability analysis. First, Steady-State Operability Model for analyzing system operability at steady-state, see Chapter 5, Section 5.2. Second, Dynamic Operability Model for analyzing system operability at dynamic state, see Chapter 5, Section 5.3.

iii. Reconfigurability in the design of networked engineering system is based decision-tree structure Wang and co-authors (Wang, et al., 2017), cDSP construct Shang and co-authors (Shang, et al., 2018), and game theoretical approach. The strategy for reconfiguration supports the repeated systemic reconfiguration, see Quadrant 4 in Figure 1.12. Three models are developed to support reconfirmation strategy. First, Reconfigurable Machining Tool Strategy for reconfiguration of tools in the manufacturing process, see Chapter 6, Section 6.2. Second, Reconfigurable Inspection System for reconfiguration of the inspection system according to needs of the manufacturing processes, see Chapter 6, Section 6.3. Third, Reconfigurable Manufacturing System as a combination of machine and inspection system, see Chapter 6, Section 6.4.

The steps of the proposed computational framework presented in Figure 3.8 are:

***Step A***. Adaptable Concurrent Realization of Networked Engineering Systems (ACRONES) as a subset of the Design for Dynamic Management computational framework. The first step is to identify the flexible design parameters, establish their connectivity, and represent the process by a comprehensive state space model. The second step is to determine the interconnections between MMP modules and the mathematical representation of the complete system. Full mathematical representation is presented in Milisavljevic and co-authors (Milisavljevic, et al., 2017). The third step is to explore the solution space for appropriate solutions to the design problem. The last step is to identify and manage different types of uncertainty, exploring solution space, and identifying robust solutions to the design problem.

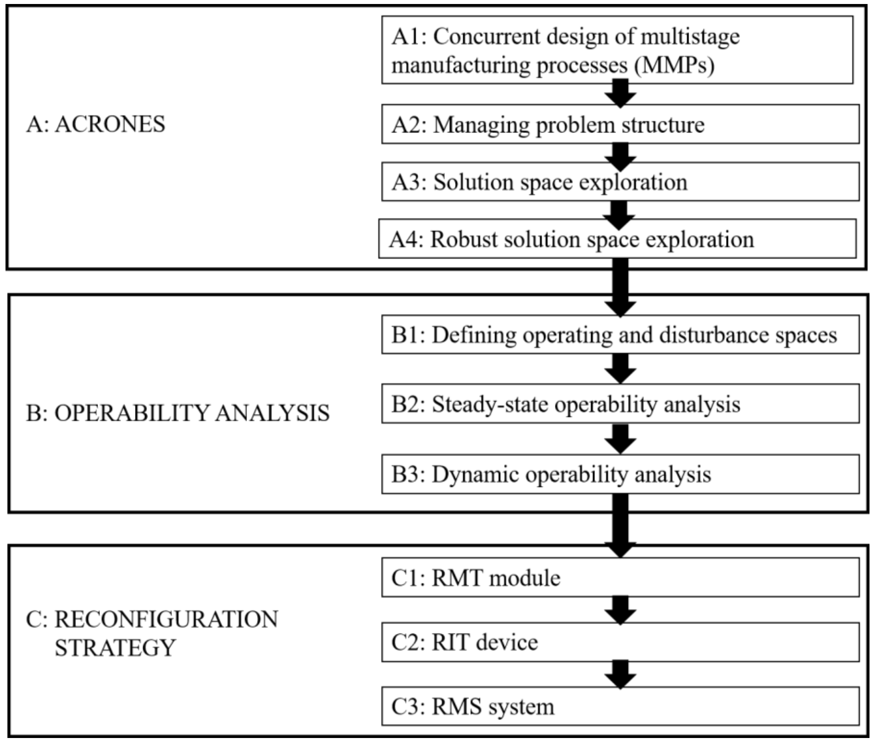



**Figure 3.8. Design for Dynamic Management of Networked Engineering System**

***Step B***. Operability Analysis. The first step, Step B1, of the operability analysis is to connect the output ranges of solutions from ACRONES to input operability spaces of the operability analysis, and output robust ranges of solutions from ACRONES to input operability disturbance spaces in the operability analysis, see Figure 3.8. The second step, Step B2, of the operability analysis steady-state operability analysis. In this step exploration of (a) original system design and obtain input ranges of original system design that gives functional system; and (b) variant system design and obtain a set point for design is taking place. Last step, Step B3, of the operability analysis is dynamic operability analysis in order to explore: (a) functional system due to natural changes in the system over time; and (b) functional system due to change in the requirements. For more information about the operability analysis in dynamic management see Chapter 5.

***Step C***. Reconfiguration Strategy. The first step, Step C1, of the reconfiguration strategy is to determine the module library and module of Reconfigurable Manufacturing Tool (RMT) in order to obtain device configuration for the next step. The second step, Step C2, is to use device configuration in order to determine the sub-system configuration of Reconfigurable Inspection Tool (RIT). Last step, Step C3, is to use sub-system configuration from the previous step in order to determine system configuration of Reconfigurable Manufacturing System (RMS). For more information about the reconfigurability strategy in dynamic management see Chapter 6.

## 3.5 Theoretical Structural Validity

In this section, the theoretical structural validity of the decision-based design computational framework, Design for Dynamic Management, is presented. The mathematical construct and the structure of the proposed computational framework are followed using simple examples. Confidence in the soundness of the proposed computational framework is established, and the utility and limitation of the proposed computational framework are checked.

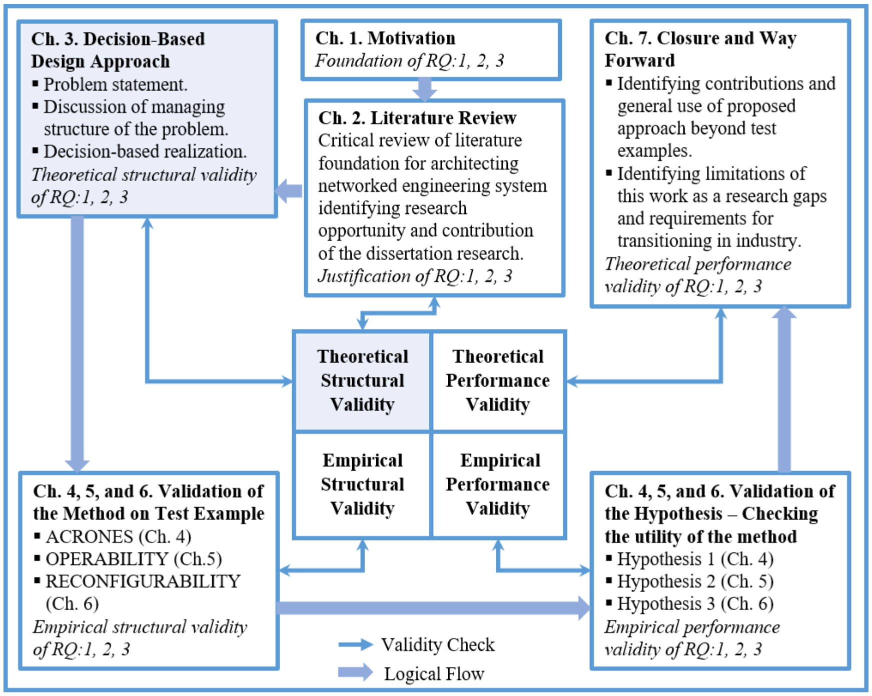



**Figure 3.9. Validation Square Roadmap**

Chapter 3 falls in quadrant one of the validation square, see Figure 3.9, where the following topics are addressed (1) problem statement, research gaps, and test examples are presented in Section 3.1; (2) problem formulation, critical evaluation of existing methods and selection of same is presented in Section 3.2; (3) discussion about the mathematical foundation of models is presented in Section 3.3; and (4) discussion about the general structure of the proposed computational framework is presented in Section 3.4.

## 3.6 Synopsis of Chapter 3

In Section 3.1, the problem of design of networked engineering systems adaptable to dynamic changes is defined, where research gaps, introduced and defined through research questions in Chapter 1, are identified. Further, the test examples are presented, Section 3.1.3. The problem is formulated as the cDSP construct in Section 3.2. The mathematical background of adaptability, operability and reconfigurability models are considered and explained in Section 3.3. The proposed decision-based design computational framework is presented in Section 3.4. The validation of the proposed computational framework in the form of the validation square is presented in Section 3.5.

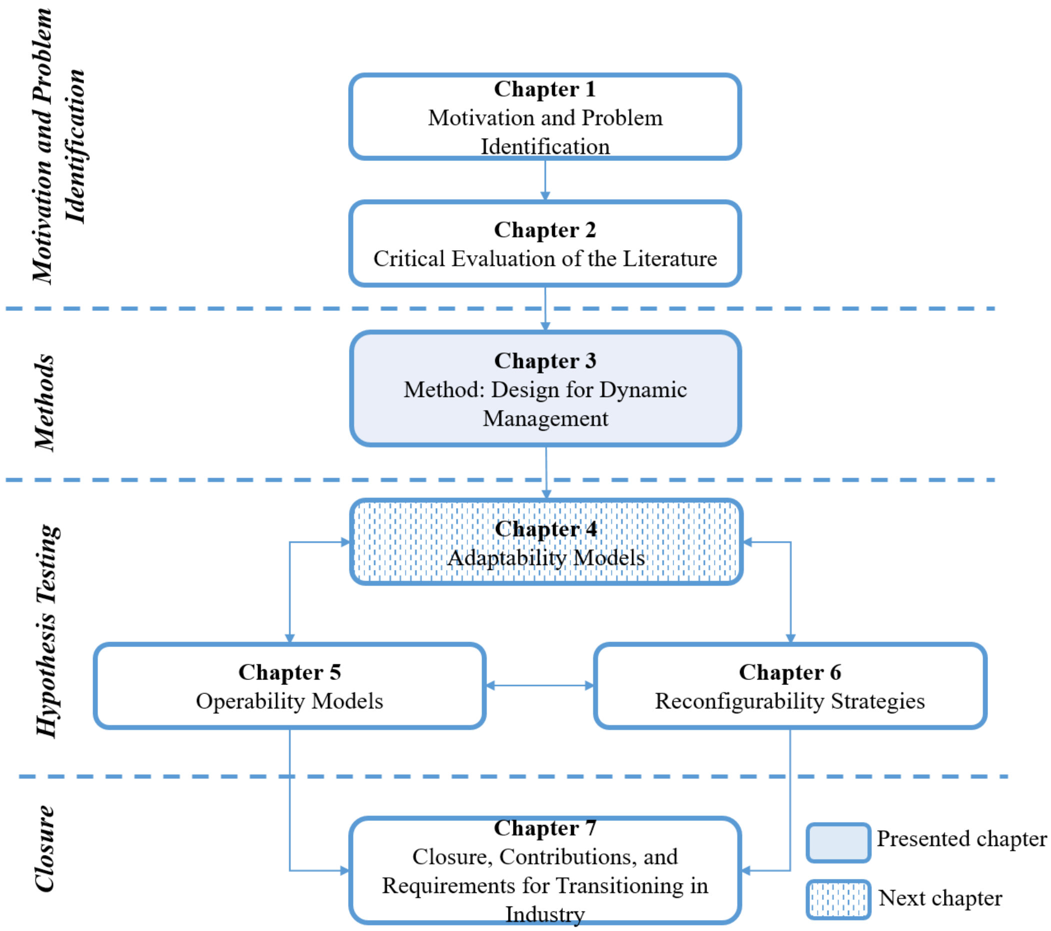



**Figure 3.10. Organization of the Dissertation – Presented and Next Chapter**

In the following chapters, see Figure 3.10, the proposed computational framework is verified. Further, in Chapter 4 adaptability models are considered for (robust) solution space exploration, operability models for system functionality analysis in Chapter 5, and reconfigurability models for reconfigurability of the engineering system in Chapter 6.

# CHAPTER 4

# ADAPTABLE CONCURRENT REALIZATION OF NETWORKED ENGINEERING SYSTEMS (ACRONES)

In this chapter, a method, Adaptable Concurrent Realization of Networked Engineering Systems (ACRONES), is presented an answer to the Research Question 1 introduced in Chapter 1, Section 1.4, and justified through critical literature review in Chapter 2, Section 2.1. The adaptability problem in the design of networked engineering systems is introduced in Chapter 3, Section 3.1. ACRONES is a component of a computational framework, Design for Dynamic Management, presented as highlighted quadrant in Figure 4.1. Further, in this chapter four different issues are addressed in the design of networked engineering systems (1) inserting flexibility at design time, (2) managing high complexity, (3) exploring a solution space, and (4) managing uncertainty. The efficacy of the method is demonstrated using a 2-D panel stamping process in N - stations as Illustrative Example 1, Chapter 3, Section 3.1.3.

The proposed adaptable concurrent design method is presented in Section 4.1 with a focus on the appropriate selection of sensors and managing computational complexity in MMP design. While the method described here is flexible and can accommodate different or additional constraints on the MMP, two commonly used constraints, diagnosability, and controllability, are used to validate the approach. The compromise Decision Support Problem formulation of a two-dimensional automobile panel stamping process in N-stations is used to demonstrate the proposed method, Section 4.2. Discussion of the results regarding the process cost and dimensional quality of a product and cost-quality tradeoffs is presented in Section 4.3. Lastly, the summary of Chapter 4 is presented in Section 4.4

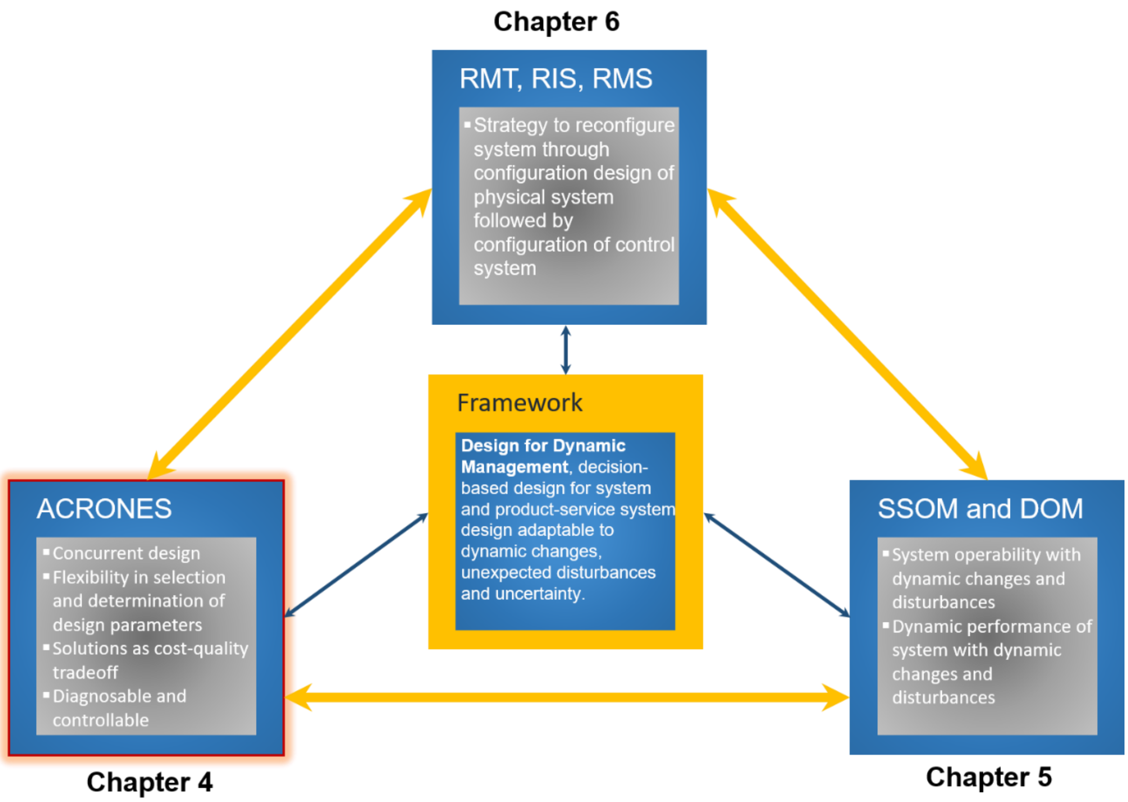



**Figure 4.1. ACRONES in Design for Dynamic Management**

## 4.1 Adaptable Concurrent Realization of Networked Engineering Systems (ACRONES)

The proposed method for adaptable concurrent design and analysis of multistage manufacturing is carried out in four steps, Figure 4.2.

- ***Step A.*** Identifying flexible design parameters, establishing their connectivity, and representing the process with a comprehensive state space model, Section 4.2.1;
- ***Step B.*** Determining interconnections between MMP modules and the mathematical representation of the complete system, Section 4.2.2;
- ***Step C.*** Exploring the solution space for appropriate solutions, Section 4.2.3; and
- ***Step D.*** Identifying and managing different types of uncertainty, exploring solution space, and identifying robust solutions to the design problem, Section 4.2.4.

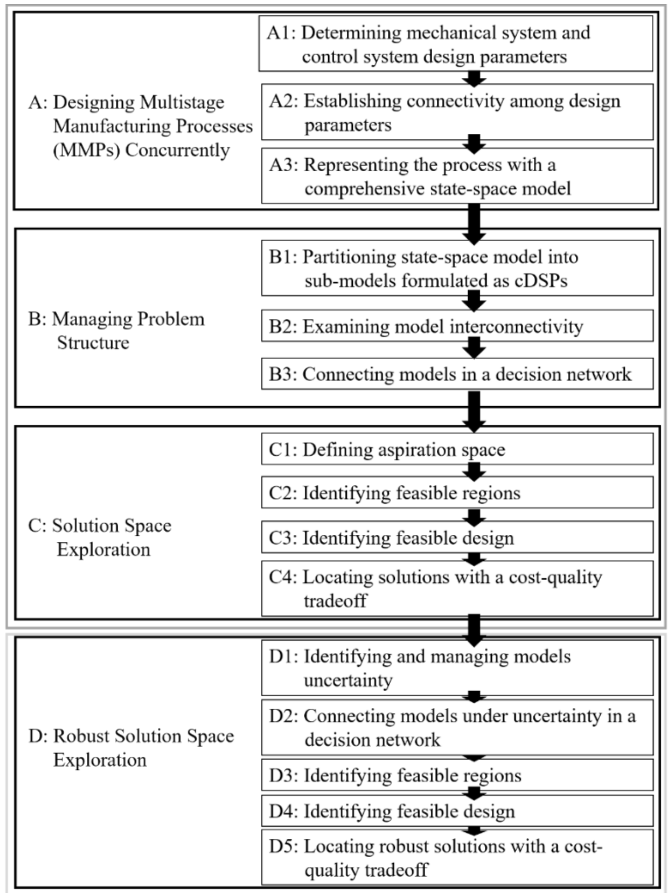



**Figure 4.2. Adaptive Concurrent Realization of Manufacturing Systems (ACRONES) Framework**

### 4.1.1 Designing Networked Engineering Systems Concurrently

The concurrent design of a mechanical system and a control system of the MMP includes the following three steps:

- ***Step A1.*** Determining the system variables of the mechanical and control systems. Most common design parameters of the mechanical system are related to tools (type, number, and position of tools) and operational stations. Design parameters of the control system are related to sensors (type, number, and position of sensors) and sensing stations.
- ***Step A2.*** Establishing connectivity among design parameters. For example, there are both fixture locators and sensors on operational stations. The relationship

between the design parameters and the dynamic behavior of the MMP during runtime is expressed in the state-space form, Figure 1.7.

- ***Step A3.*** Representing the process with a comprehensive state-space model. The relationships in Step A2 result in models that are often distinct from one another. These models have to be unified to obtain a description of the complete MMP. In this study, the propagation of variations in the output of each process is considered using the 'Stream of Variation (SoV)' approach (Jin and Shi, 1999). An overall system description in the state-space form is determined using this approach, Section 4.2.

### 4.1.2 Managing Problem Structure

The state-space model developed in Step A3 of Section 4.1.1 is computationally complex and usually requires a large number of variables to represent the process. Solving such a problem is not straightforward and often is computationally expensive. The steps to manage the complexity of the mathematical representation are:

- ***Step B1.*** Partitioning the state-space model, Step A3, into sub-models formulated as cDSPs. These can be process decision models (diagnosability, controllability) or models to estimate overall cost (Izquierdo et al., 2007), the lower part of Figure 1.7. The cDSPs for diagnosability, controllability, and cost (models D, C and E) are described in Milisavljevic, 2015. Process decision models are used to represent the effect of design decisions on the cost of the process. Further, a performance observation model (cDSP), PM in Figure 1.7, is used to estimate the output quality of the product.

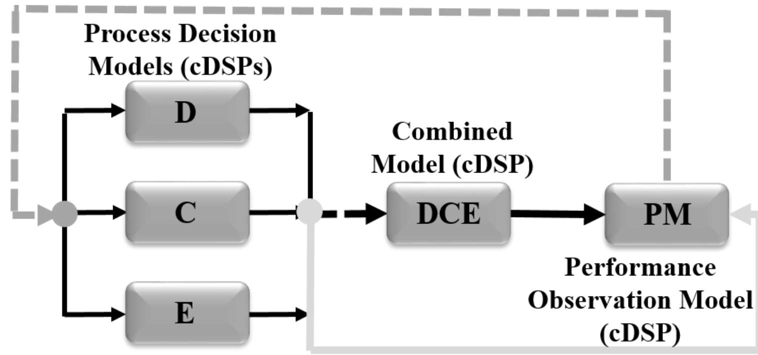



**Figure 4.3. Connecting Process Decision and Performance Observation Models with a Decision Network Structure**

- ***Step B2.*** Establishing interconnectivity between the SoV and the cDSP models. The foundation of process decision and performance observation models is a comprehensive state-space model (SoV), upper part of Figure 1.7. However, these models are partitioned from the comprehensive state-space model, upper part of Figure 1.7, and represented as cDSPs, lower part of Figure 1.7. Further, process decision and the performance observation models have the same mechanical and a control system characteristics and system matrices. For instance, process decision models (D, C, E) have the same inputs, the same numbers of parts assembled, $n_p$, can have the same errors introduced in the process $m_k$ and different outputs ($\mu, \mu_c$, etc.) that can be interfaced with a performance observation model to measure the size of variations, Figure 1.7.

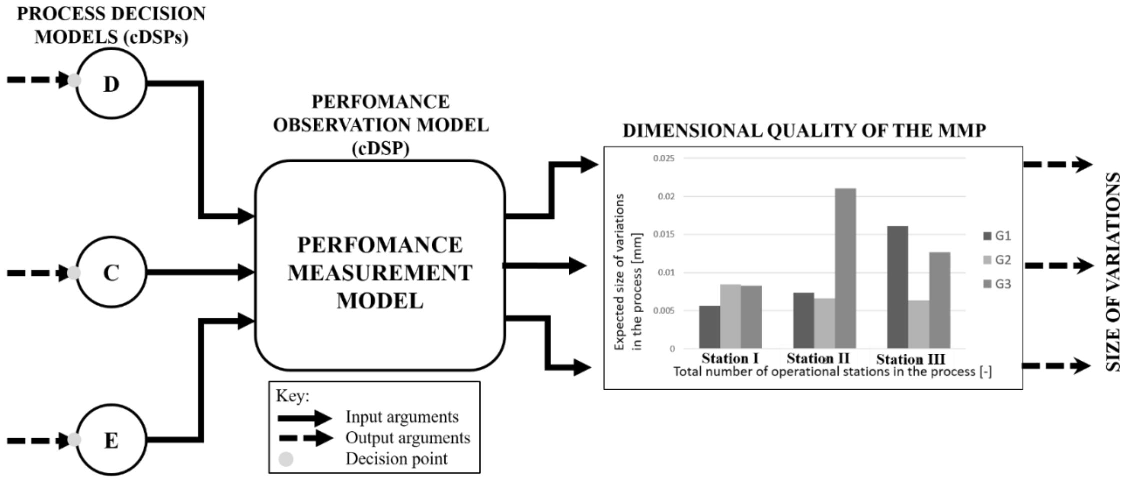



**Figure 4.4. Measuring Size of Variations with Performance Observation Model**

- ***Step B3.*** Connect all cDSPs in a decision network, Figure 4.3. To accomplish Step B3, first a decision network is developed to identify a possible solution for the MMP design criteria and determine its effect on the overall cost. For instance, decisions such as sensing characteristics directly influence the cost of the process, light gray link in Figure 4.3, and different numbers of sensors or types of sensors entails different costs. If design constraints such as number of tools and their position, process diagnosability and controllability are satisfied, the process decision models are integrated, dashed black link in Figure 4.3, and the process of searching for additional solutions that are diagnosable, controllable and cost-effective continues. The combined network model is used to integrate individual cDSPs such as diagnosability, controllability, cost-effectiveness, DCE in Figure 4.3. If there is no feasible solution to the overall MMP design problem, the next step is to return to the process decision models, dashed gray link in Figure 4.3, knowing which process decision models must be reconfigured.

The next step is to measure the size of variations by connecting the combined model with a performance observation model, continuous black link in Figure 4.3. Since the process decision models are connected with the performance observation model, Figure 4.4, design decisions have a direct influence on process cost, Figure 4.3, and indirect on product dimensional quality. The output of process decision models, continuous black link in Figure 4.4, such as the number and position of sensors, sensor distribution scheme, and the number of sensing stations is the input to the performance observation model where the size of variations at each station is measured, the right side of Figure 4.4. Further, the output from the performance observation model, dashed black link in Figure 4.4, is the size of variations associated with the process quality. If the size of variations lies within prescribed limits, the decision point is reached, the gray point in Figure 4.4, and process decision models are integrated into the combined model, DCE in Figure 4.3. However, if the size of variations is above prescribed limits, then appropriate process decision models have to be reconfigured. Finally, all the feasible solutions are consolidated and a solution space exploration procedure, Section 4.3.3, is employed to choose the best solution.

### 4.1.3 Solution Space Exploration

In the proposed method solutions are determined to be a tradeoff between the process cost and product quality, i.e., size of variations in products. A strategy for identifying and exploring a possible solution space in the design of the MMP is:

- ***Step C1.*** Defining an aspiration space by setting up the goals for a particular case. The aspiration space is framed by a designer's wishes. For instance, a designer may wish to minimize variations in product dimensions or at least keep them within the range -0.8 [mm] and 0.8 [mm] while minimizing process cost.

- ***Step C2.*** Identifying model interconnectivity by determining regions where feasible designs exist based on satisfying constraints and bounds or where they might exist by minimizing constraint violation.
- ***Step C3.*** Identifying feasible designs from the neighborhood of feasible or near feasible regions, frame the boundary of the feasible design space using a preemptive representation of the goals (Smith, et al., 2015).
- ***Step C4.*** Locating solutions as a cost-quality tradeoff, having refined an understanding of the cDSPs, process decision models' feasible design space and the regions of greatest interest in Step C3, move along the extreme values generating deeper understanding by exploring tradeoffs by using an Archimedean (weighted sum) formulation of the goals as indicated by Smith and co-authors (Smith, et al., 2015). Regions of great interest are guided by what is most important to a design engineer, such as process cost, quality, etc. The goal is to minimize the deviation function, i.e., the distance between the aspiration space and feasible design space. The proposed method is iterative and in each iteration, the deviation function is minimized and good solutions are located.

### 4.1.4 Robust Solution Space Exploration

In the early stages of design models may be incomplete, inaccurate, and with unequal fidelity and there is a need to consider different types of uncertainty to make the final design immune to uncertainties. However, in the design of MMPs it is difficult to identify and manage different types of uncertainty in different models, therefore, exploring a solution space and locating robust solutions is a challenging task. A strategy for identifying and exploring a possible solution space in the design of MMPs is:

- ***Step D1.*** Solution space exploration, Step C in Section 4.1., leads to gaining insight into the process characteristics. In MMP, uncertainty management, raises concerns such as unpredictability of both mechanical and control system, whether parameters of a given model are subject to variations associated with variations of attributes of the tools and sensors of systems, imprecise processes, the lack of knowledge about some processes, the lack of knowledge about models and information propagation through a chain of models, and the necessity of exploring alternatives.

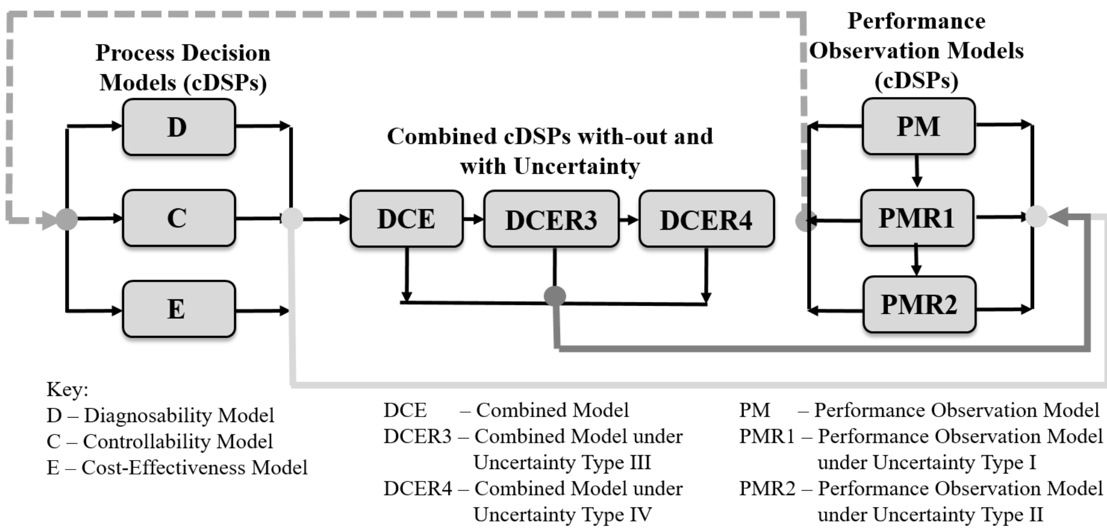



**Figure 4.5. Connecting cDSPs with and without Uncertainty with a Decision Network Structure (Milisavljevic-Syed, et al., 2018)**

- ***Step D2.*** In Step D1 different types of uncertainty are identified and managed. In Step D2 all cDSPs with uncertainty are connected in a decision network, Figure 4.5. A decision network is proposed in Step B3 to identify a possible solution for the design criteria for the MMP under uncertainty and its effect on the overall cost.

The next step is to connect the combined model without uncertainty, DCE in Figure 4.5, and the combined model with uncertainty Type III, DCER3 in Figure 4.5, and Type IV, DCER4 in Figure 4.5, with the performance observation model without uncertainty, PM in Figure 4.5, and the performance observation model with uncertainty Type I, PMR1 in Figure 4.5, and Type II, PMR2 in Figure 4.5, continuous dark gray link in Figure 4.6. Since the combined models relate to the performance observation model, design decisions such as attributes of the tools and sensors have a direct influence on the cost of the process, Figure 4.5, and an indirect effect on the quality of the process, Figure 4.6. The output of the combined models, continuous black link in Figure 4.6, such as the number and the position of sensors, distribution of sensors in the process, and the number of sensing stations is the input to the performance observation models where the size of variation in the N-stage process for each station is measured. Further, the outputs from the performance observation models, dashed black link in Figure 4.6, are the sizes of variations which determine the quality of the process. If the size of variations is within prescribed limits, the decision point is shown by the light gray point in Figure 4.6, and the search for robust solutions continues. Finally, all the feasible solutions are consolidated and a solution space exploration procedure (Steps D3 – D5) is employed to pick the preferred solution.

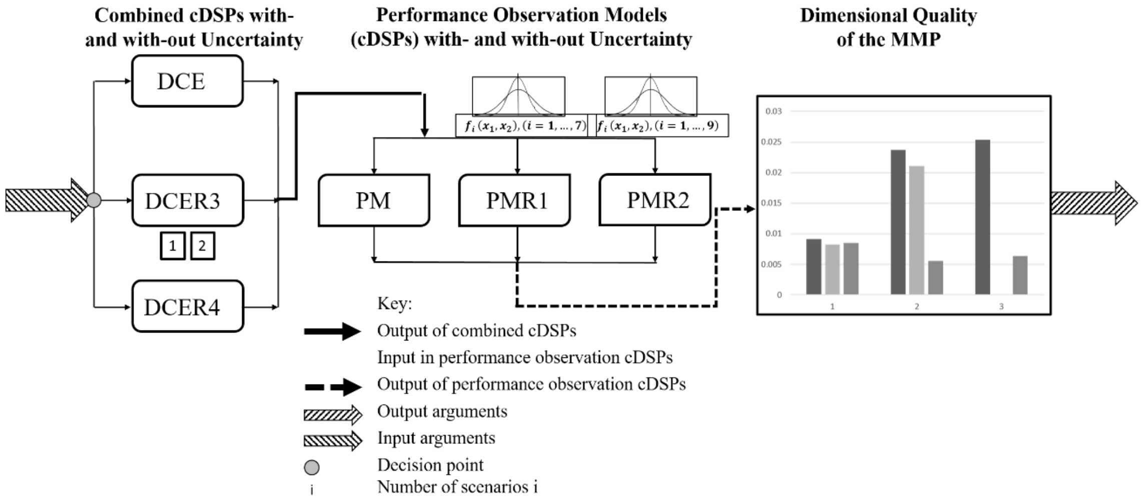



**Figure 4.6. Measuring the Size of Variations with Performance Observation Models with and without Uncertainty**

- ***Step D3.*** Identify model interconnectivity by determining regions where feasible designs exist based by satisfying the constraints and bounds or where they might exist by minimizing constraint violation.
- ***Step D4.*** Identify feasible designs in the neighborhood of feasible or near feasible regions, framing the boundary of the feasible design space using a preemptive goal formulation (Ding, et al., 2003).
- ***Step D5.*** Locate solutions as a cost-quality tradeoff, as previously explained in Step C4. The proposed method is iterative and in each run, the deviation function is minimized, and good robust solutions are located.

Multistage manufacturing systems are not inherently diagnosable and controllable but rather need to be designed to be so and there is more than one way of accomplishing this. If the model of the system is known and accurate than it is easy to design both diagnosable and controllable system. However, if the model of the system is unknown or inaccurate than the solution space will change. Further, if there is uncertainty in the process how is it possible to identify the right solution? The problem addressed and resolved with the ACRONES method is how to determine tooling and sensing arguments to design a system that is cost-effective, diagnosable and controllable, and that has a solution which is robust even in the presence of uncertainty.

The compromise Decision Support Problem (cDSP) formulation of the adaptable concurrent model is presented in Section 4.2, and results and discussion is presented in Section 4.3., where smaller process decision models and combined model with and without uncertainty are presented in Sections 4.3.1 – 4.3.3.

## 4.2 The Compromise Decision Support Problem Formulation

The cDSP construct is used to describe MMP in state-space form, see Equations 3.1 and 3.2. The MMP-cDSP is a superset of diagnosability, controllability, and cost-effectiveness cDSP models and is obtained by combing the three cDSPs, Figure 1.7 in Section 1.3 The comprehensive state-space model for the test example considered in Section 3.2.2 has 8 system variables and 16 constraints. The design problem is determining the minimum number of sensing stations and sensors, and an adequate sensor distribution scheme, use of PTs control actions, and sensing penalties in order to satisfy constraints (4), (6), (14), and (15) and to minimize overall process cost.

**Given**

| | | | |
|---|---|---|---|
| *Known* | Number of operational stations in the process | N | [-] |
| | Number of parts in the stamping | $n_p$ | [-] |
| | Number, and the position of fixture points in the process | $P_i$ | [-; x, z] |
| | Potential number, and the position of sensors in the process | $M_{Pi}$ | [-; x, z] |
| | Dimensional quality (size of variations) boundary values are set | $y_k$ | [mm] |
| *Assume* | A 3-2-1 fixture is used | | |
| | All parts used in the process are rigid | | |
| | Sum of system goals weight coefficients are equal | | |

**Find**

| | | |
|---|---|---|
| Total number of sensors | $M_{Pi}$ | [-] |
| Sensors distribution in the process per station | $M_{i,k}$ | [-] |
| Total number of sensing stations | $M_S$ | [-] |
| Use of PT`s control actions in the process regarding cost-effectiveness | $PT$ | [-] |
| Total sensing penalties in the process | $P$ | [-] |
| Deviation variables | $d_i^-, d_i^+$ (i=1,…,4) | [-] |

**Satisfy**

Constraints

| | | |
|---|---|---|
| C1 Desired process diagnosability index | $\mu_D = 1$ | [%] |
| C2 Desired process controllability index | $\mu_C = 1$ | [%] |
| C3 System variables weight coefficients has to be equal to 1, regarding the cost-effectiveness, which ties in Eq. 9 | $c_1 + c_2 + c_3 + c_4 = 1$ | [-] |
| C4 Sum of system goals weight coefficients has to be equal to 1 | $w_1 + w_2 + w_3 = 1$ | [-] |
| C5 Fixture points $P_i$ and $P_j$ cannot have the same position (i, j =1,…, 8) | $P_{i,x} \neq P_{j,x}, P_{i,z} \neq P_{j,z}$ | [mm] |
| C6 Sensors points $M_i$ and $M_j$ cannot be the same points (i, j =1,…, 20) | $M_{i,x} \neq M_{j,x}, M_{i,z} \neq M_{j,z}$ | [mm] |
| C7 No three sensors can be collinear in x- and z-direction | $M_{i,x} \neq M_{j,x} \neq M_{r,x}$, $M_{i,z} \neq M_{j,z} \neq M_{r,z}$ | [mm] |
| C8 Fixture points $P_1, P_2, P_3, P_4, P_7, P_8$ must be collinear in z- direction | $P_{1,z} = P_{2,z} = P_{3,z} = P_{4,z} = P_{7,z} = P_{8,z}$ | [mm] |
| C9 Fixture points $P_5, P_6$ must be collinear in z-direction | $P_{5,z} = P_{6,z}$ | [mm] |
| C10 Product of deviation variables equal 0 | $d_i^- \times d_i^+ = 0$ | [-] |

Goals

| | | |
|---|---|---|
| G1 Minimize cost of the process | $(c_1 \cdot M_{Pi} + c_2 \cdot M_S + c_3 \cdot \mathrm{PT} + c_4 \cdot P) + d_1^- - d_1^+ = 1$ | [-] |
| G2 Maximize quality of the process | $\left(-\sum_{k=1}^{N} [\bar{y}_k^T \cdot Q_k \cdot \bar{y}_k]\right) + d_2^- - d_2^+ = 1$ | [-] |

Goal $G_1$ is normalized and its value is between $0 \leq G_1 \leq 100$. Coefficients $c_j$ $(j = 1, \cdots, 4)$ are monetary costs where $\sum_{j=1}^{4} c_j = 1$.

Bounds

| | | |
|---|---|---|
| B1The total number of sensors has to be between 0 and 20 | $0 \leq M_{Pi} \leq 20$ | [-] |
| B2 Distribution of sensors per station | $0 \leq M_{i,k} \leq 8$ | [-] |
| B3 Total number of sensing stations has to be between 0 and 4 | $0 \leq M_S \leq 4$ | [-] |
| B4 Use of control actions has to be between 0 and 1 | $0 \leq PT \leq 1$ | [-] |
| B5 Sensing penalties has to be between 0 and 2 | $0 \leq P \leq 2$ | [-] |

| | | |
|---|---|---|
| B6 Dimensional variations at station | $-0.8 \le y_k \le 0.8$ | [-] |
| B7 Overall cost | $0 \le \text{Cost} \le n$ | [$] |
| B8 Deviation variables have to be greater than or equal to 0 | $d_i^-, d_i^+ \ge 0$ | [-] |

**Minimize**

The deviation function (Z): Archimedean formulation

$$Z = min \sum_{i=1}^{3} (W_i d_i^- + W_i d_i^+); \ \sum_{i=1}^{3} W_i = 1; \ W_i \ge 0$$

The results and discussion of the adaptable concurrent model is presented in Section 4.3., where smaller process decision models and combined model with and without uncertainty are presented in Sections 4.3.1 – 4.3.3.

## 4.3 Results and Discussion

As discussed in Milisavljevic-Syed and co-authors (Milisavljevic-Syed, et al., 2018) the specification of system variables and their effect on the overall MMP cost is difficult to ascertain prior to implementation. For the sake of illustration, five sensors are assumed to be available for use in the MMP. Solution space exploration involves undertaking a cost-quality tradeoff, Section 4.1.3, that is why the results regarding the process cost, Section 4.3.1, the process quality, Section 4.3.2, and cost-quality tradeoff, Section 4.3.3, are presented in this section. All results are obtained through simulation in MATLAB.

### 4.3.1 Cost of the Process

The data obtained by exercising the ACRONES is used by a designer to frame a design space based on feasible bounds. This gives us the insight into the selection of design parameters (total number of sensors, sensing stations, and their distribution) that are diagnosable, controllable and cost-effective, and how this influences the process cost even under uncertainty. The cost of the process refers to the number of sensors and sensing stations, programmable tooling control actions used in the process and sensing penalties due to minimized number of sensing stations.

In this study, we are considering the cost of the process of process decision models, D, C, E in Figure 4.3, and combined comprehensive model without and with uncertainty, DCE, and DCER3 in Figure 4.5.

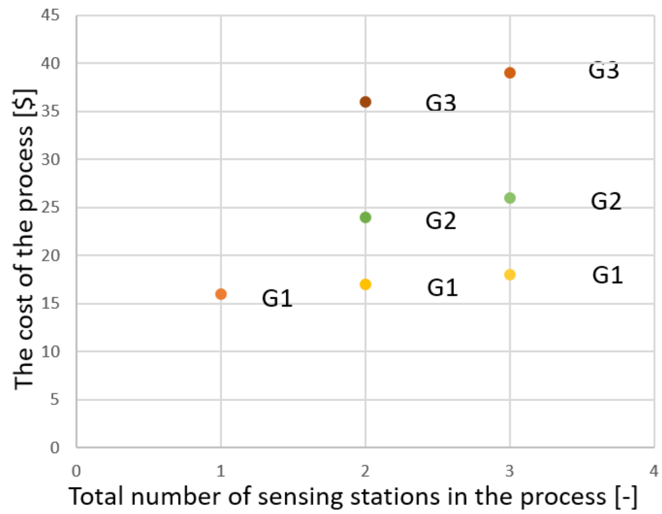



**Figure 4.7. Cost of the Feasible Designs According to Diagnosability, Controllability, and Cost-Effectiveness Models**

In process decision models three different models are considered: (1) G1 – minimizing sensing cost regarding diagnosability; (2) G2 – minimizing sensing cost regarding controllability; and (3) G3 – minimizing sensing and tooling cost regarding both diagnosability and controllability, Figure 4.7. If one sensing station, $M_S$, is implemented design G1 is achieved when the process cost is $16. If two sensing stations, $M_S$, are implemented all three goals are achieved where process cost for G1 is $17, G2 is $24, and G3 is $36. If three sensing stations, $M_S$, are implemented in design all three goals are achieved where the process cost for G1 is $18, G2 is $26, and G3 is $39. The process cost with respect to goals, G1 - G3, is presented in Appendix, Table A.1, where it can be seen the process cost is increasing with the increase of sensing stations in the process and the highest cost occurs when three sensing stations are present.

The cost of the process between the combined model without uncertainty, DCE in Figure 4.5, and the combined model with uncertainty, DCER3 in Figure 4.5, are summarized in Appendix A, Tables A.4 – A.6. In this section, the cost of the process for feasible design is compared in DCE (Milisavljevic-Syed, et al., 2018), and DCER3 for two scenarios, DCER3_Q and DCER3_C (Milisavljevic, et al., 2017).

The solution space of DCE is presented in Appendix A, Table A.2. Further, with the use of two sensing stations, the total number of sensors is between 4 and 12, and 256 solutions are available. On the other hand, with the use of three sensing stations in the process, the total number of sensors is between 5 and 20, and 65,280 solutions are available.

The solution space of DCER3_Q is presented in Appendix A, Table A.3. Further, with the use of two sensing stations, the total number of sensors is between 5 and 11, and 64 solutions are available. On the other hand, with the use of three sensing stations in the process, the total number of sensors is between 6 and 19, and 16320 solutions are available.

The solution space of DCER3_C is presented in Appendix A, Table A.4. Further, with the use of two sensing stations, the total number of sensors required is between 4 and 5, and 8 solutions are available. On the other hand, with the use of three sensing stations in the process, the total number of sensors is limited to 5, and 8 solutions are available.

The cost of the process is lower for DCER3_Q and DCER3_C than for the combined DCE. Further, with use of two sensing stations and four sensors in the process, the cost of the process for the combined DCER3_C is $19, Table A.4, where for DCE is $26, Table A.2. With the use of two sensing stations and five sensors in the process cost of the process for DCE is $31, Table A.1, for DCER3_Q is $30, Table A.3, and for DCER3_C is $23, Table A.4. With the use of three sensing stations and five sensors in the process cost of the process for DCE is $34, Table A.2, and for DCER3_C is $23, Table A.4.

In summary, the feasible design space is wider for DCE than it is for DCER3_Q and DCER3_C. However, the cost of the process is lower once uncertainty is inserted in DCE as previously discussed. The lowest cost is achieved with DCER3_C when two sensing stations and four sensors are used in the design of MMPs. It can be concluded that the cost of the process depends on sensors distribution and cost can be reduced with adequate distribution of sensors in the process.

### 4.3.2 Quality of the Process

The dimensional accuracy of manufactured components is an important measure of process quality. Therefore, to incorporate this into MMP design, the cDSP model is augmented with the performance observation model (Milisavljevic, 2015), to determine the expected size of process variations. Two questions need to be answered (1) "Will dimensional quality increase with increasing sensing stations in the process?"; (2) "Will dimensional quality increase once uncertainty is inserted into the combined model?".

In order to answer the first research question process decision models, D, C, E in Figure 4.4, are connected with performance measurement model, PM in Figure 4.4.

If one sensing station, $M_S$, is used it is seen that the expected size of variations, $y_k$, is measured only for G1, Figure 4.8. However, dimensional quality is maintained within prescribed boundaries since the size of variations is minimized and close to 0 [mm] in the end-of-line of the process. Further, it can be concluded that if a system is designed to be only diagnosable then this is an adequate solution with the lowest cost, Appendix A, Table A.1, and with satisfactory dimensional quality, Figure 4.8.

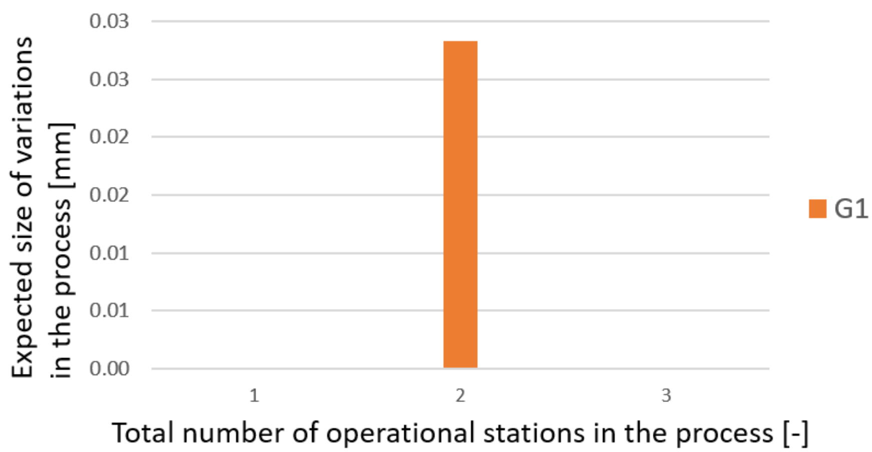



**Figure 4.8. Expected Size of Variations in the Process with One Sensing Station**

If two sensing stations, $M_S$, are used in the process the expected size of variations, $y_k$, is measured for all 3 goals, Figure 4.9. The expected size of variations for G1, first rectangle in Figure 4.9, at Station 3 is 0.015 [mm], for G2, second rectangle in Figure 4.9, at Station 3 is 0.01 [mm], and for G3, third rectangle in Figure 4.9, at Station 3 is 0 [mm].

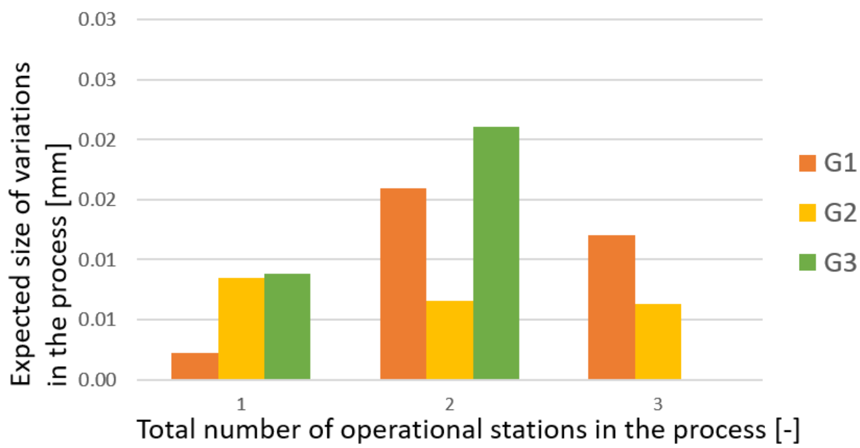



**Figure 4.9. Expected Size of Variations in the Process with Two Sensing Stations**

If three sensing stations, $M_S$, are used in the process it can be seen that the expected size of variations is measured, $y_k$, for all 3 goals, Figure 4.10. The expected size of variations for G1, first rectangle in Figure 4.10, at Station 3 is 0.02 [mm], for G2, second rectangle in Figure 4.10, at Station 3 is 0.01 [mm], and for G3, third rectangle in Figure 4.10, at Station 3 is 0.015 [mm].

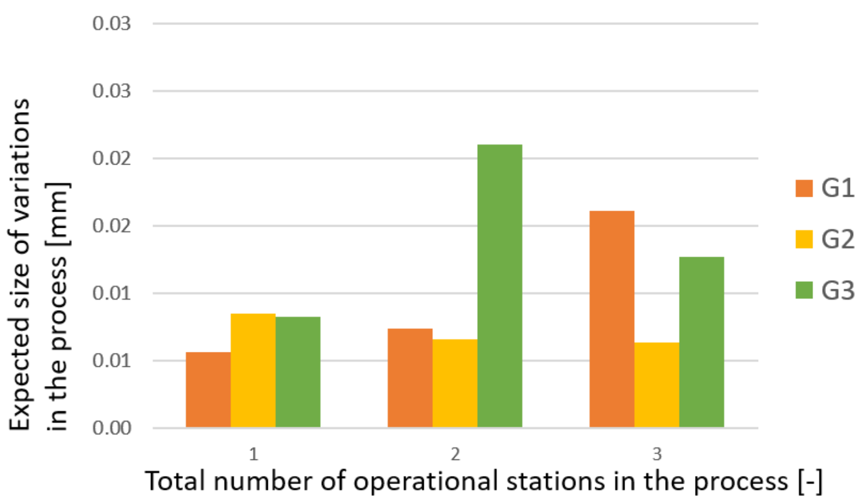



**Figure 4.10. Expected Size of Variations in the Process with Three Sensing Stations**

The size of variations is much lower when two sensing stations are used in the process, regarding diagnosability, G1, and cost-effectiveness, G3, Figure 4.9. However, there is no difference in controllability if variations sizes when two or three sensing stations are used, G2, Figures 4.11 and 4.12. Furthermore, dimensional quality is not improved by increasing the number of sensing stations but rather by the adequate selection of design parameters and sensor distributions.

In order to answer the second research question, the combined model without, DCE in Figure 4.6, and with, DCER3 in Figure 4.6, uncertainty are connected with performance observation model, Figure 4.6.

If two sensing stations and four sensors are used in the process the size of variations is higher when uncertainty is present in DCE. Further, the size of variations is 2.56E-06 [mm] of DCE, Table A.2, and 2.57E-06 [mm] of DCER3_C, Table A.4. On the other hand, if two sensing stations and five sensors are used in the process, the size of variations is lower when uncertainty is present in DCER3_Q. Further, the size of variations is between 2.56E-06 – 0.011195 [mm] of DCE, Table A.2 and Figure 4.9, 2.56E-06 [mm] of DCER3_Q, Table A.3 and Figure 4.10, and between 2.60E-06 – 0.011195 [mm] of DCER3_C, Table A.4. However, if three sensing stations and five sensors are used in the process the size of variations is higher when uncertainty is applied in DCE. Further, the size of variations is 2.56E-06 [mm] of DCE, Table A.2 and Figure 4.9, and between 2.59E-06 – 2.60E-06 [mm] of DCER2_C, Table A.4.

In summary, dimensional quality is not improved by increasing the number of sensing stations, Figures 4.10 – 4.12, but rather by the adequate selection of the design parameters and sensor distributions. Further, the size of end-of-line variations, Table A.1, are much lower when two sensing stations are used in the process regarding goals Gi, (i = 1 - 3). The amount of additional complexity associated with adding stages to the manufacturing process grows linearly and does not depend on the level process parallelization. Further, if the size of variations of DCE, Table A.2, is compared with DCER2_Q, Table A.3, it can be concluded that the size of variations is lower once model simplifications are made in DCE that is quality orientated. Therefore, the answer to the question is that dimensional quality will increase once uncertainty is present in DCE as long the simplification made in DCE is quality orientated.

### 4.3.3 The Cost-Quality Relationship Analysis

In this section, the relationship between the cost and the quality of the process is addressed and solutions are located, as indicated in Step D5 in Figure 1.7, with use of 5 sensors and 2 – 3 sensing stations in the process. Further, if one sensing station is used in the process then there are no feasible designs according to DCE and DCER3. However, if two or three sensing stations are used in the process there are feasible designs for DCE and DCER3, see Figure 4.11.

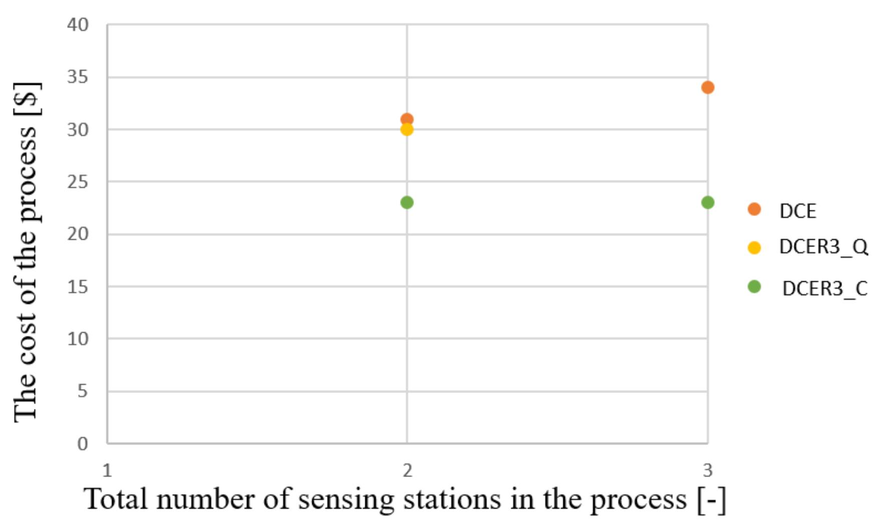



**Figure 4.11. Cost of the Feasible Designs According to DCE and DCER3**

The cost of the process is lower for DCER3 than for DCE, Figure 4.11. The lowest cost of the process is for DCER3_C where simplification made in DCE are cost orientated, dark gray dots in Figure 4.11.

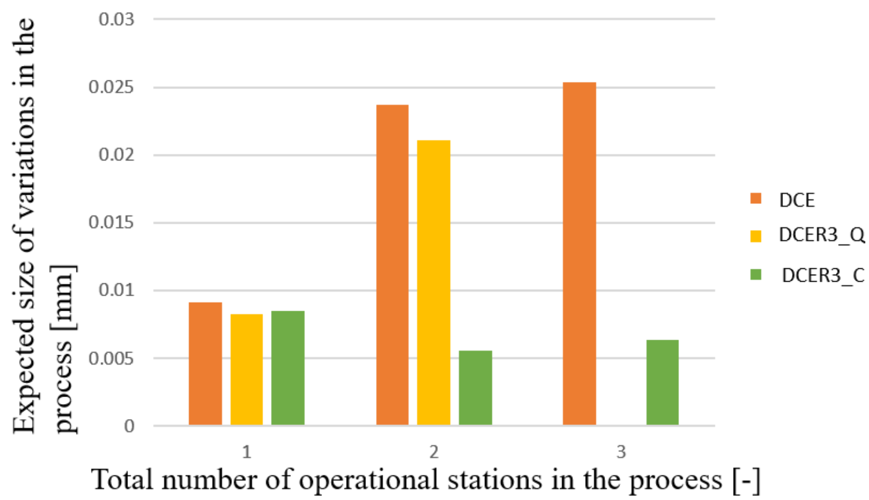



**Figure 4.12. Expected Size of Variations in the Process with Two Sensing Stations**

If two sensing stations are used in the process, then the size of variations are increasing up to 0.025 [mm] in Station 3 for DCE, black rectangles in Figure 4.12, decreasing to 0 [mm] in Station 3 for DCER3_Q, light gray rectangles in Figure 4.12, and decreasing to 0.006 [mm] in Station 3 for DCER3_C, dark gray rectangles in Figure 4.12.

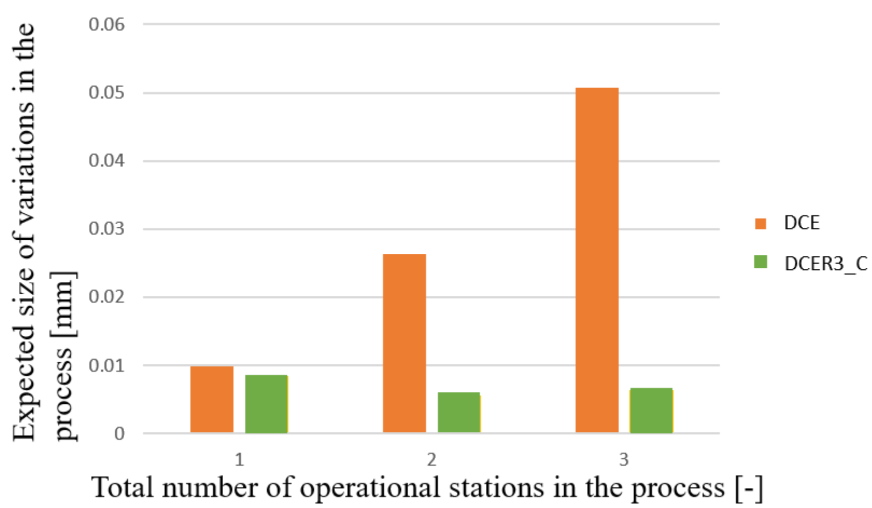



**Figure 4.13. Expected Size of Variations in the Process with Three Sensing Stations**

If three sensing stations are used in the process, then the size of variations are increasing in the process to 0.052 [mm] in Station 3 for DCE, black rectangles in Figure

4.13, and decreasing to 0.006 [mm] in Station 3 for DCER3_C, dark gray rectangles in Figure 4.13.

In summary, the cost-quality relationship regarding DCE and DCER3 leads to the following observations (1) the cost of the process is higher with the use of three sensing stations than with two sensing stations with the same number of sensors in the process, (2) the feasible design space is larger for DCE than it is for DCER3_Q and DCER3_C, (3) the cost of the process depends on the distribution of sensors and cost can be reduced with the adequate distribution of sensors in the process, (4) the cost of the process is reduced once uncertainty is included in DCER3_Q and DCER3_C, (5) the dimensional quality is improved with use of two sensing stations in the process regarding DCER3_Q and the dimensional quality is maintained within desirable boundaries with use of three sensing stations in the process regarding DCER3_C. It can be concluded that once uncertainty is inserted in DCE the results are improved regarding process cost and quality. Furthermore, the most favorable solutions are achieved with DCER3_Q so that cost is reduced, quality is improved, and all constraints are satisfied when two sensing stations and five sensors are used in the process. Dimensional quality is improved once uncertainty is inserted in DCE when the simplifications made in DCE are quality orientated.

## 4.4 Synopsis of Chapter 4

In this chapter, Empirical Structural and Performance Validity of the Research Question 1 "*What is the computational framework in the design method that facilitates adaptable design in the realization of networked engineering systems?*" is addressed. The answer is the method *Adaptable Concurrent Realization of Networked Engineering*

*Systems* (ACRONES). The empirical structural validity of the method, Quadrant 2 of the Validation Square, is presented in Sections 4.1 and 4.2. The empirical performance validity of the method, Quadrant 3 of the Validation Square, is presented in Section 4.3.

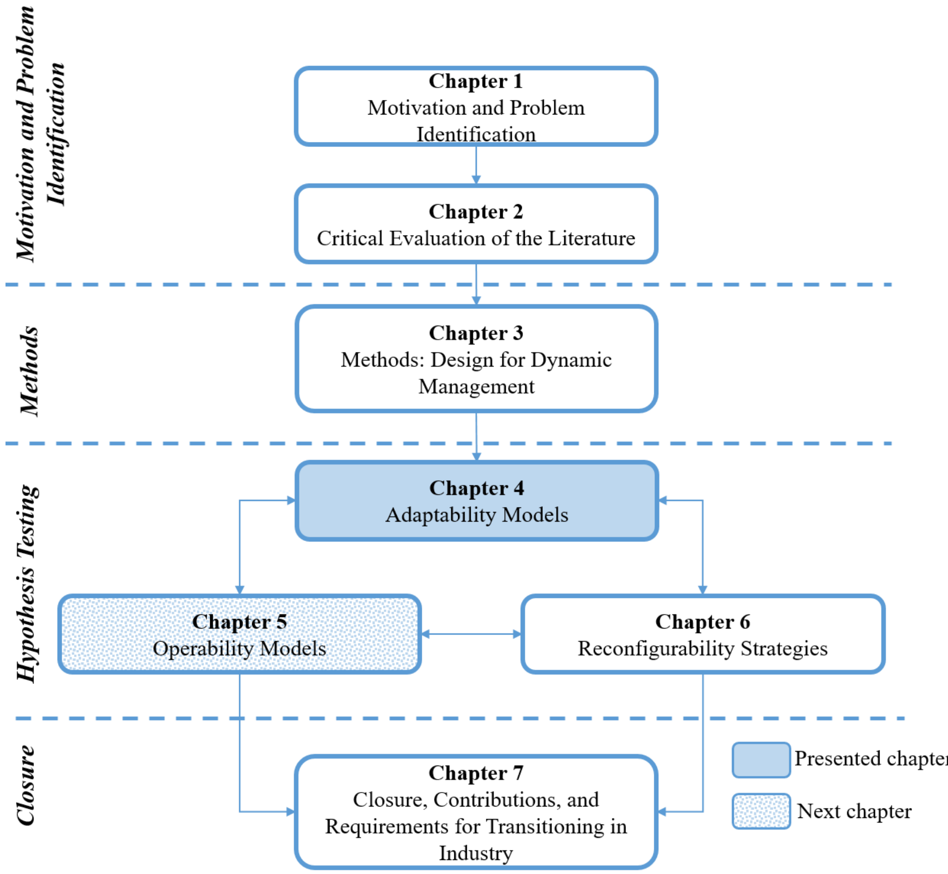



**Figure 4.14. Organization of the Dissertation – Presented and Next Chapter**

In Chapter 5, Figure 4.14, the second part of the problem, Chapter 3, Section 3.1, is addressed regarding system functionality with a change in the requirements. The operability models for system analysis are presented, the second quadrant in Figure 4.1. A Steady-State Operability Model (SSOM) for system functionality when a system is in steady state, Section 5.1. A Dynamic Operability Model (DOM) for the dynamic performance of the system, Section 5.2.

# CHAPTER 5

# OPERABILITY ANALYSIS IN THE REALIZATION OF NETWORKED ENGINEERING SYSTEMS

In this chapter, a method for operability analysis is presented as answer to the second part of the problem in design of networked engineering systems, determining the functionality of the system undergoing dynamic change, is presented an answer to the Research Question 2 introduced in Chapter 1, Section 1.4, and justified through critical literature review in Chapter 2, Section 2.2. The operability problem in the design of networked engineering systems is introduced in Chapter 3, Section 3.1. The operability analysis method is a component of the computational framework, *Design for Dynamic Management,* presented as highlighted quadrant in Figure 5.1. Further, two different issues are addressed in the operability analysis (1) functionality of engineering systems undergoing dynamic changes in steady-state, and (2) dynamic performance of the system undergoing dynamic changes. The efficacy of the method is demonstrated using a 2-D panel stamping process in N - stations as an Illustrative Example 1, Chapter 3, Section 3.1.3, and a continuous stirred tank reactors as an Illustrative Example 2, Chapter 3, Section 3.1.3.

In Section 5.1, Operability Analysis Method in Design for Dynamic Management is presented. In Section 5.2, the Steady-State Operability Model (SSOM) is presented. In Section 5.3, the Dynamic Operability Model (DOM) is presented. In Section 5.4, results of SSOM and DOM are presented and the usefulness of the methods is discussed. Lastly, summary of Chapter 5 is presented in Section 5.5.

## 5.1. Operability Analysis in Design for Dynamic Management

Operability analysis method is a component of the computational framework, Design for Dynamic Management, where functionality of the system is analyzed undergoing dynamic change. Ranges of solutions obtained by exercising the ACRONES, Chapter 4, are input in the operability analysis method. There are two different models in the operability analysis method (1) Steady-state Operability Model (SSOM), Section 5.1, and (2) Dynamic Operability Model (DOM), Section 5.2. In Chapter 2, Section 2.2, frame of reference is presented.

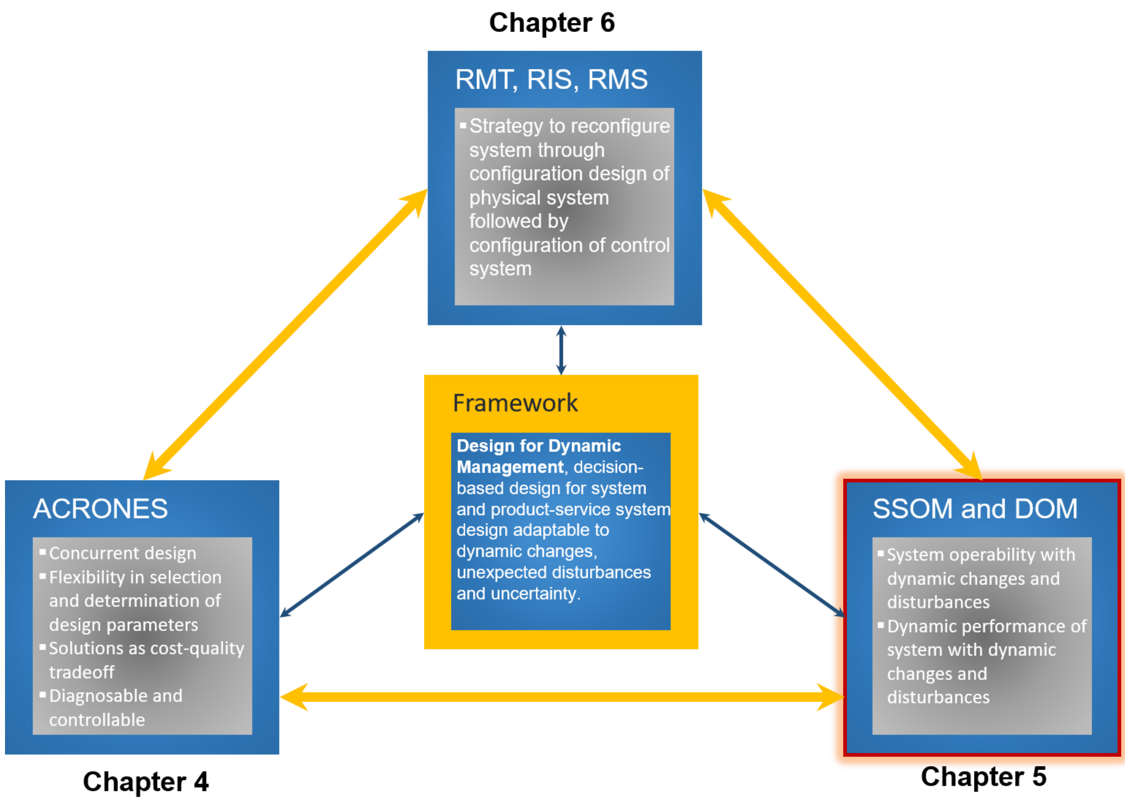



**Figure 5.1. Operability Analysis in Design for Dynamic Management**

In this work operability analysis is connected with the Adaptable Concurrent Realization of Networked Engineering System (ACRONES) method, presented in Chapter 4, the first quadrant in Figure 5.1. Exercising the ACRONES ranges of solutions and robust solutions without domain knowledge are obtained. The ACRONES output is the input in the operability analysis method, see Figure 5.2, where operability spaces and disturbance operability spaces are defined. Whether system is functional in its steady or dynamic state is determined with operability analysis. The output information from operability analysis goes back to the ACRONES in order to explore different ranges of solutions and robust solutions. However, if there is no functional solution (steady or dynamic state) then next step is reconfiguration strategy, presented in Chapter 6, the third quadrant in Figure 5.1. Functional system design for steady-state systems is explored with Steady-State Operability Model (SSOM) and verified with 2-D panel stamping process as Illustrative Example 1, presented in Section 5.1. Functional system design for dynamic systems is explored with Dynamic Operability Model (DOM) and verified with continuously stirred tank reactors as Illustrative Example 2, presented in Section 5.2. Results and discussion are presented in Section 5.3.

The Steady-State Operability Model (SSOM) and Dynamic Operability Model (DOM) as part of Operability Analysis in Design for Dynamic Management is presented in Sections 5.2 and 5.3.

## 5.2 Steady-State Operability Model

The Steady-State Operability Model (SSOM) gives a designer insights that supports design process of a new or the existing system. The use of compromise DSP in the operability ensures that distances between Desired Input Space (DIS) and Achieved Input Space (AIS), Desired Output Space (DOS) and Achieved Output Space (AOS) are minimized, see Figure 5.3. Furthermore, the SSOM is connected with the ACRONES method where preliminary design information are generated in order to help designer frame the operability spaces (AIS, AOS, DOS, and DIS), see Figure 5.3. For detailed explanation about the ACRONES method see Chapter 4, Section 4.1. For detailed information about the operability spaces see Section 3.3.2.

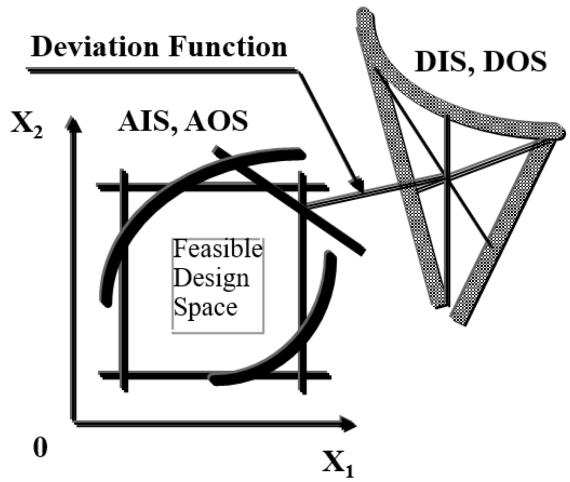



**Figure 5.2. Solution Space Exploration**

The SSOM is examining the level of achievement of designer expectations for variant design of a system (SOIOS) or for original design of a system (SOIIS), the regulatory operability of the process insensitive to disturbances for variant design of a system (ROI) or for original design of a system (ROI), and the overall operability of a system (OI) in steady-state. The solution algorithm is presented in Figure 5.3.

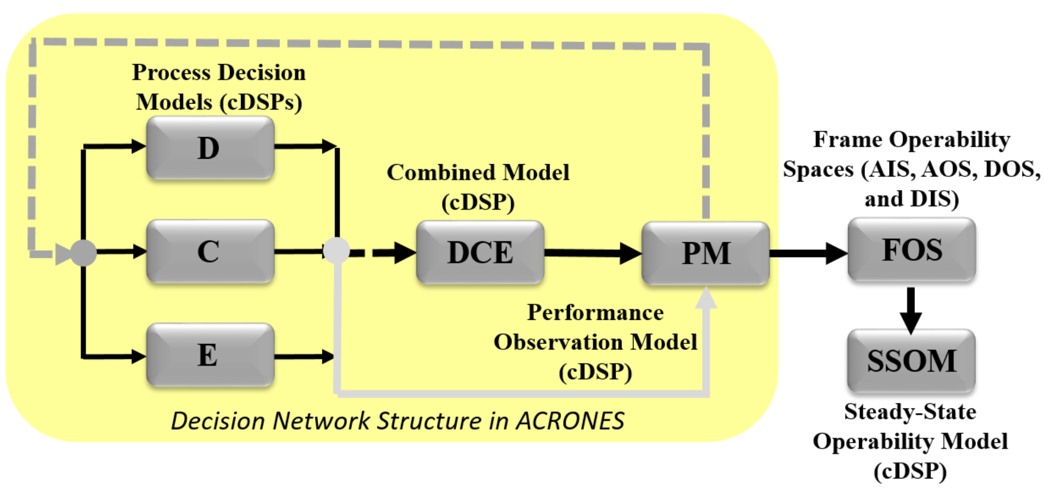


**Figure 5.3. Connecting the ACRONES with the SSOM**

The solution algorithm, Figure 5.4, provides an elegant and efficient way to explore the solution space and identify possible solutions of operable system[1)]. The solution scheme includes the following steps:

1. Obtain information from the ACRONES and frame the operability spaces.
2. Examine the Servo Operability Index in the Output Space (SOIOS) for the variant design of a system, see Equation 3.12 in Section 3.3.2, or the Servo Operability Index in the Input Space (SOIIS) for original design of a system, see Equation 3.13 in Section 3.3.2. The SOIOS and SOIIS values are between 0 and 1. If the value is below 1 for the SOIOS then designer expectations are greater than designed process can deliver and redesign is required. If the value is below 1 for the SOIIS then there is a need to increase the available ranges of some of the inputs and redesign is required.
3. Examine the regulatory operability of the process in order to determine the anticipated ranges of disturbances. In original system design, see Equation 3.14 in Section 3.3.2, region of disturbances is based on the available input space (AIS) that needs to be higher than the desired input space (DIS). In variant system design, see Equation 3.15 in Section 3.3.2, region of disturbances is based on the Tolerable Disturbance Space (TDS) that needs to be higher than the Expected Disturbance Space (EDS), see Section 3.3.2. The Regulatory Operability Index ROI values are between 0 and 1. If the value is below 1 for the ROI of the original system design then the range of AIS needs to be loosen and redesign is required. If the value is below 1 for the ROI of the variant system design then the range of TDS needs to be loosen and redesign is required.

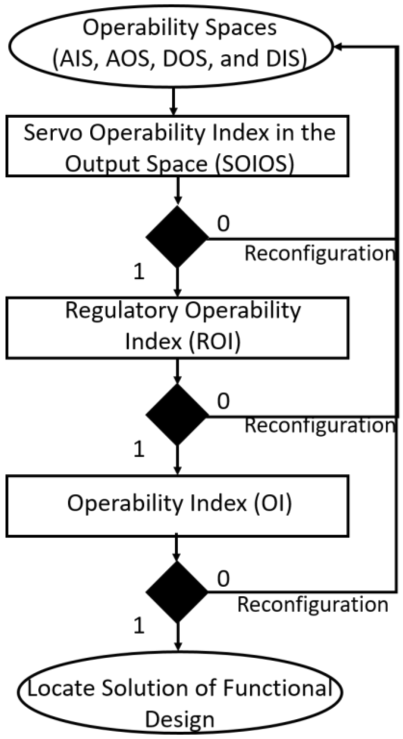



**Figure 5.4. Solution Scheme**

4. Examine the Operability Index (OI) of the system in the steady-state, see Equation 3.16 in Section 3.3.2. The OI values are between 0 and 1, where values bellow 1 implies that designed system is not operable and redesign is required. If OI is equal to 1 than solutions of functional design are located.

The use of compromise DSP and ACRONES in the steady-state operability is novel approach. For detailed information about computational framework, Design for Dynamic Management, see Chapter 3, Section 3.4.

### 5.2.1 The cDSP for the Steady-State Operability Model

The word formulation of the cDSP construct for the Steady-State Operability model supported by mathematical expressions is presented in this section. The cDSP construct has been extended in order to accommodate the operability analysis in system design. The construct is as follows. ***Given*** that information about alternatives, assumptions, system parameters, and other relevant information are generated with ACRONES, designer have enough information to frame the operability spaces (DIS, AIS, DOS, AOS) and process disturbances (TDS, EDS). Second step is to ***Find*** independent *system variables* that describe the physical attributes of operability spaces and process disturbances that describes goals, and the values of the *deviation variables* that indicate the extent to which the goals (SOIOS, SOIIS, ROI, OI) are achieved. Third step is to ***Satisfy*** *system constraints, system goals* (SOIOS, SOIIS, ROI, OI), and *system bounds*. Lastly, ***Minimize*** *deviation function* which is a measure of the deviation of the system performance from desired one (DOS, DIS) to actual one (AOS, AIS).

*cDSP Construct for the Steady-State Operability Analysis*

**Given**

- An alternative that is to be improved through modification.
- Assumptions used to model the domain of interest.
- The system parameters.
- All other relevant information.

| | |
|---|---|
| n | number of system variables |
| p+q | number of system constraints |
| p | equality constraints |
| q | inequality constraints |
| m | number of system goals |
| $g_i(X)$ | system constraint function $g_i(X) = C_i(X) - D_i(X)$ |
| $f_k(d_i)$ | function of deviation variables to be minimized at priority level k for the preemptive case |
| $W_i$ | weight for the Archimedean case |

Information generated with the ACRONES help designer frame the operability spaces and process disturbances:

- Desired Input Space (DIS)
- Achieved Input Space (AIS)
- Desired Output Space (DOS)
- Achieved Output Space (AOS)
- Tolerable Disturbance Space (TDS)
- Expected Disturbance Space (EDS)

**Find**

- The values of the independent *system variables* (they describe the physical attributes of an artifact).

  $X_j$ $\quad j = 1,..., n$

- The values of the *deviation variables* (they indicate the extent to which the goals are achieved).

  $d_i^-, d_i^+$ $\quad i = 1,..., m$

- System variables that describe SOIOS, SOIIS, ROI, OI.
- The values of the *deviation variables* (they indicate the extent to which the goals SOIOS, SOIIS, ROI, OI are achieved).

**Satisfy**

- The *system constraints* that must be satisfied for the solution to be feasible.

**Existing System Design** **New System Design**

- There is no restriction placed on linearity or convexity.

$g_i(X) = 0;$ $i = 1,..., p$
$g_i(X) \geq 0;$ $i = p+1,...,p+q$

- The *system goals* that must achieve a specified target value as far as possible.
- There is no restriction placed on linearity or convexity.

$A_i(X) + d_i^- - d_i^+ = G_i$ $i = 1,..., m$ ;

- The lower and upper *bounds* on the system.

$X_j^{min} \leq X_j \leq X_j^{max};$ $j = 1,..., n$
$d_i^-, d_i \geq 0$ and $d_i^- \cdot d_i^+ = 0$

- Servo Operability Index in the Output Space: SOIOS

$$= \frac{\mu[AOS_u(d^N) \cap DOS]}{\mu[DOS]}$$

- Regulatory Operability Index:

$$ROI = \frac{\mu[TDS \cap EDS]}{\mu[EDS]}$$

- Servo Operability Index in the Input Space: SOIIS

$$= \frac{\mu[AIS \cap DIS_y(d^N)]}{\mu[DIS_y(d^N)]}$$

- Regulatory Operability Index: $ROI$

$$= \frac{\mu[AIS \cap DIS_d(y^N)]}{\mu[DIS_d(y^N)]}$$

- Operability Index (OI):

$$OI = \frac{\mu[AIS \cap DIS]}{\mu[DIS]}$$

**Minimize**

The *deviation function* which is a measure of the deviation of the system performance from that implied by the set of goals and their associated priority levels or relative weights:

- Case a: Preemptive (lexicographic minimum)

$Z = [\ f_1(\ d_i^-, d_i^+), . . . ,f_k(\ d_i^-, d_i^+)\ ]$

- Case b: Archimedean

$Z = \sum_{i=1}^{m} W_i(d_i^- + d_i^+);$
$\sum W_i = 1;\ \ W_i \geq 0.$

The *deviation function* which is a measure of the deviation of the system performance from that implied by the set of goals (SOIOS, SOIIS, ROI, OI) and their associated priority levels or relative weights.

### 5.2.2 Steady-State Operability Analysis in Design for Dynamic Management.

#### Different Scenarios

The test example considered to demonstrate the usefulness of the Steady-State Operability method is a 2-D Panel Stamping Process.

***Panel Stamping Process.*** Panel stamping process represents an integral part of many manufacturing processes, one of those processes is the assembly of automobile bodies. Panel stamping process represents simplification of auto body stamping process according to Apley and Shi (Apley and Shi, 1998). Further, the assumption is that the panels substitute the auto body parts with 100% dimensional accuracy. The dimensional quality of the completed product is highly dependent on the level of accuracy with which the panels are fixtured. Typically the coordinate sensors, measures the position of a part feature, are installed in the end-of-line of the process.

Four different scenarios are considered:

1. Panel assembling process in three stations with end-of-line sensing configuration, see Figure 5.5, a);
2. Panel assembling process in three stations with distributed sensing configuration, see Figure 5.5, b);
3. Panel assembling process in four stations with end-of-line sensing configuration, see Figure 5.6, a); and
4. Panel assembling process in four stations with distributed sensing configuration, see Figure 5.6, b).

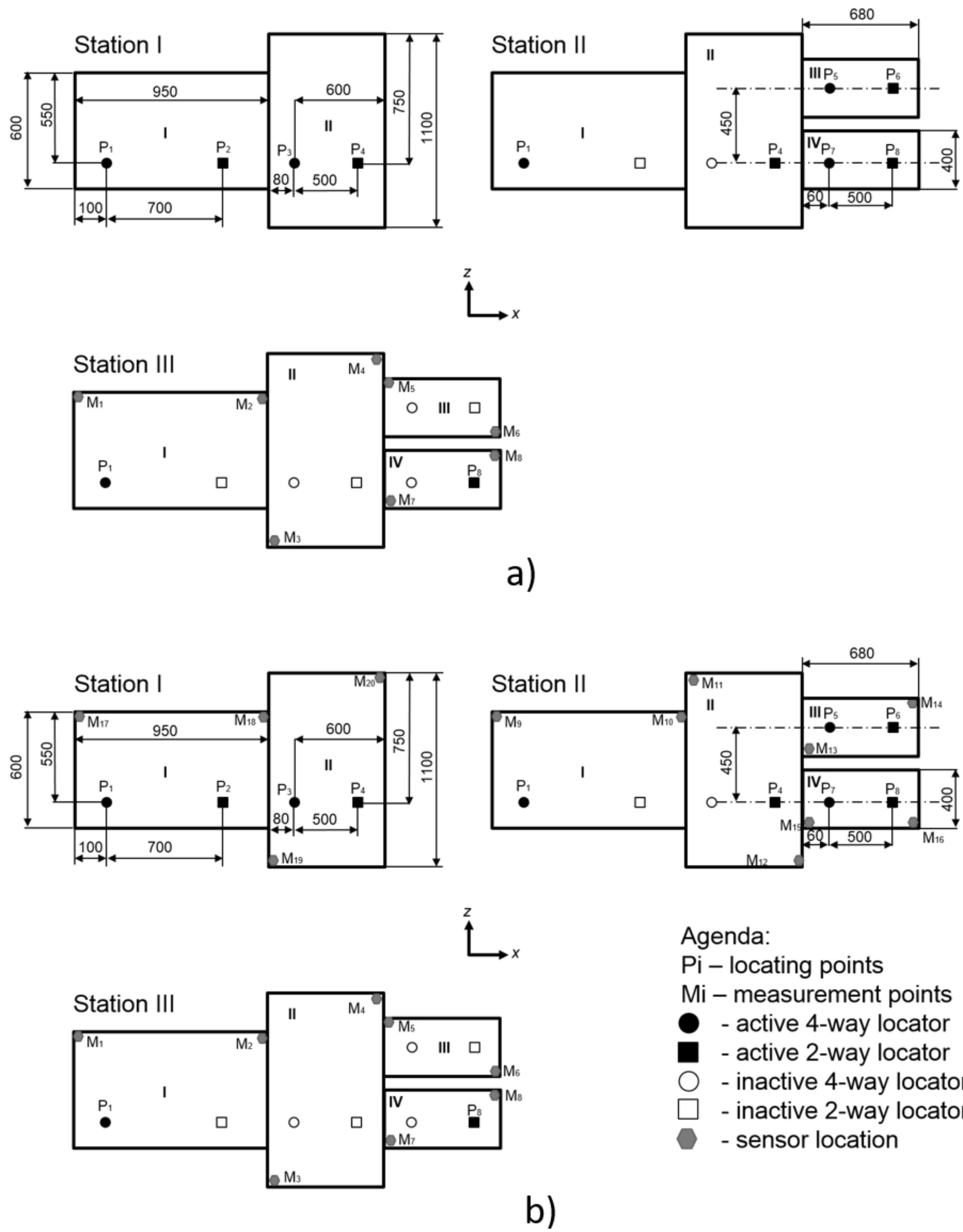



**Figure 5.5. Two-dimensional Panel Stamping Process in Three Stations (Ding, et al., 2002)**

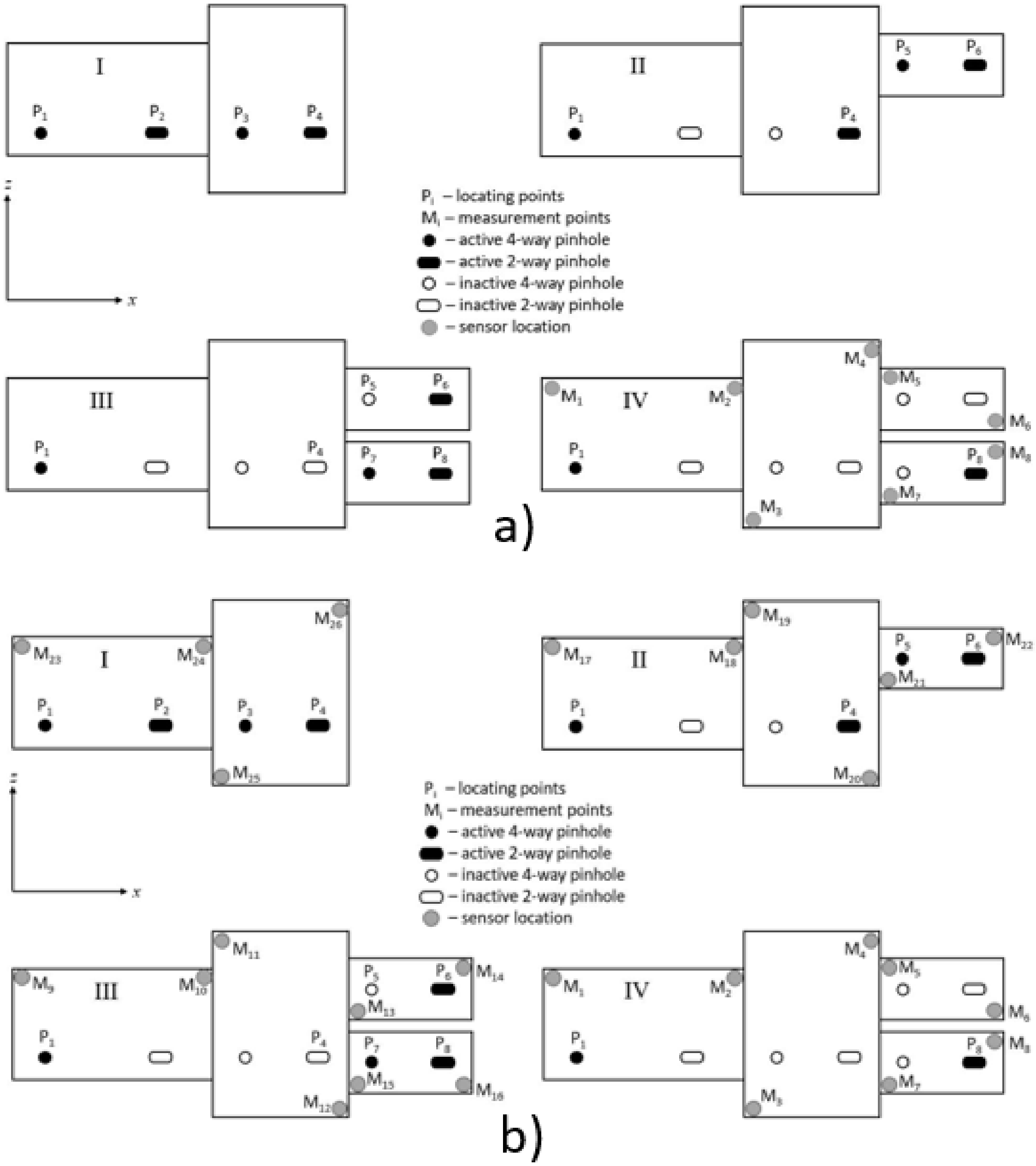



**Figure 5.6. Two-dimensional Panel Stamping Process in Four Stations**

For more information about the panel stamping process see Ding and co-authors (Ding, et al., 2002). The cDSP formulation of the Steady-State Operability Analysis of panel stamping processes is presented in Appendix B. The output of the Steady-State Operability Model (SSOM) is the input to the Dynamic Operability Model (DOM) presented in Section 5.3.

## 5.3 Dynamic Operability Model

Dynamic operability model (DOM) gives a designer insights that supports design process of the existing system given that change in requirements and/or system disturbance can happen over time. The use of compromise DSP in the dynamic operability ensures that distances between Dynamic Desired Output Space (DDOS) and desired response time $t_f^d$ and Dynamic Achieved Output Space (DAOS) are minimized, see Figure 5.7, for a given Dynamic Available Input Space (DAIS) and desired response time, $t_f$. For variant or original system design the DOM is connected with the Steady-State Operability Model (SSOM) where functionality of such system is determined through SOIOS/SOIIS, ROI, and OI, see Section 5.1.

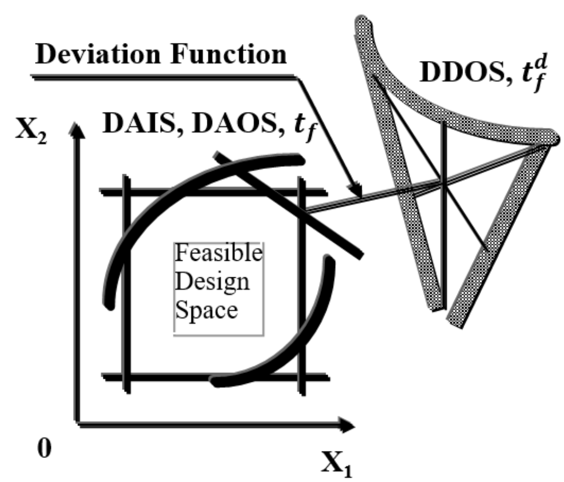



**Figure 5.7. Solution Space Exploration over Time**

Dynamic operability is defined as the shortest time it would take a system to adjust to the desired set point after a change in requirements and/or a disturbance occurrence. The operability measure is on idea that time spend away from desired set point is due to off-specification products (Milisavljevic-Syed et al., 2018). Different type of controllers, feedback, run-to-run, can be utilized to evaluate operability measure. Minimum-time optimal controller approach is defined as the minimum time for the process to overcome the worst disturbance and/or change in the requirements (Subramanian et al., 2001).

The DOM is examining the shortest time, $t_f^*(y_{sp}, d)$, of system to adjust to change in requirements, $y_{sp} \in DOS$, and/or disturbances, $d \in EDS$, that can occur over time.

The solution algorithm, Figure 5.8, provides an elegant and efficient way to explore the solution space and identify possible solutions of operable system over change in requirements and/or disturbances in system. The solution scheme includes the following steps:

1. Obtain information from the ACRONES to frame Dynamic Available Input Space (DAIS).
2. Examine the Dynamic Desired Operability Spaces (DDOS) that is giving us the desired dynamic performance of a system, see Equation 3.19 in Section 3.3.2. If the response time of the system, $t_f$, is less than or equal to desired response time, $t_f^d$, set by a designer than system has desired dynamic performance. If the response time of the system, $t_f$, is greater than desired response time, $t_f^d$, set by a designer than system does not have desired dynamic performance and reconfiguration is required.
3. Examine the Dynamic Available Operating Space (DAOS) that give us insights in dynamic performance that can be achieved by a system for a given choice of DAIS, DOS, EDS, see Equation 3.20 in Section 3.3.2. For detailed information about the DOS, and EDS see Section 5.2. If the response time of the system, $t_f$, is greater than or equal to desired time for a system to achieve stability, $t_f^*$, set by a designer than system has desired dynamic performance. If the response time of

the system, $t_f$, is greater than desired time, $t_f^*$, set by a designer than system does not have desired dynamic performance and reconfiguration is required.

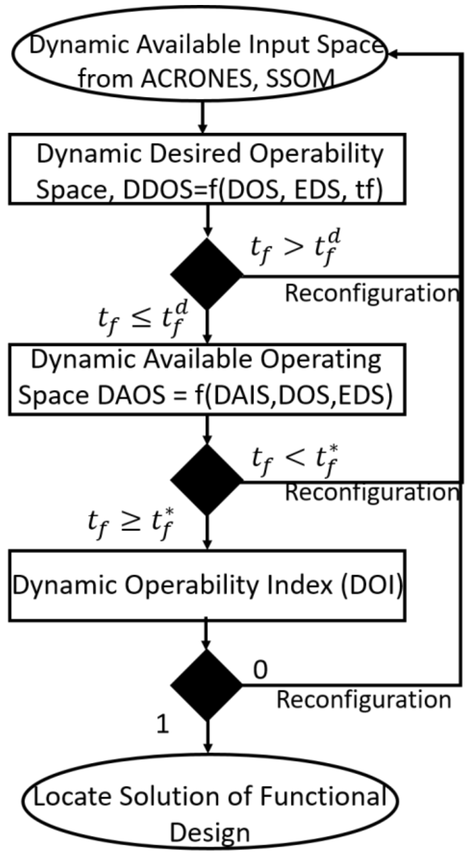



**Figure 5.8. Solution Scheme of Dynamic Operability Model**

4. Examine the Dynamic Operability Index (DOI) of the continuous system, see Equation 3.23 in Section 3.3.2. It gives us fraction of operating ranges that can be achieved within the response time, $t_f^d(y, d)$, given DAIS. The DOI values are between 0 and 1, where values bellow 1 implies that designed system is not operable due to change in requirements and/or disturbances over time and redesign is required. If DOI is equal to 1 than the best solutions of functional design are located, i.e., the upper bound of the achievable control performance of the process (Milisavljevic-Syed et al., 2018).

The use of compromise DSP and ACRONES in the dynamic operability analysis is novel approach.

### 5.3.1 The cDSP for the Dynamic Operability Model

The word formulation of the cDSP construct for the Dynamic Operability supported by mathematical expressions is presented in this section. The cDSP construct has been enriched to accommodate dynamic operability analysis. The construct is as follows. ***Given*** that information about alternatives, assumptions, system parameters, and other relevant information are generated with ACRONES and steady-state operability is examined for steady system, designer have enough information to frame the operability spaces (DAIS). Second step is to ***Find*** independent *system variables* that describe the physical attributes of dynamic operability spaces that describes goals, and the values of the *deviation variables* that indicate the extent to which the goals (DDOS, DAOS, DOI) are achieved. Third step is to ***Satisfy*** *system constraints* responses time, *system goals* (DDOS, DAOS, DOI), and *system bounds*. Lastly, ***Minimize*** *deviation function* which is a measure of the deviation of the system performance from desired one (DDOS) to actual one (DAOS, DAIS).

*cDSP Construct for the Dynamic Operability Analysis*

**Given**

- An alternative that is to be improved through modification.
- Assumptions used to model the domain of interest.
- The system parameters.
- All other relevant information.

| | |
|---|---|
| n | number of system variables |
| p+q | number of system constraints |
| p | equality constraints |
| q | inequality constraints |
| m | number of system goals |
| $g_i(X)$ | system constraint function<br>$g_i(X) = C_i(X) - D_i(X)$ |

Information generated with the ACRONES and examined with SSOM help designer frame the operability spaces (DAIS) and desired response time in case of change and disturbances:

- Dynamic Available Input Space (DAIS)
- Desired response time, $t_f^d$
- Desired time for a system to achieve stability, $t_f^*$

| | |
|---|---|
| $f_k(d_i)$ function of deviation variables to be minimized at priority level k for the preemptive case<br>$W_i$ weight for the Archimedean case | |
| **Find** | |
| ▪ The values of the independent *system variables* (they describe the physical attributes of an artifact).<br>$X_j$ $j = 1,..., n$ | ▪ System variables that describe DDOS, DAOS, DDAOS, DOEDS, DOI |
| ▪ The values of the *deviation variables* (they indicate the extent to which the goals are achieved).<br>$d_i^-, d_i^+$ $i = 1,..., m$ | ▪ The values of the *deviation variables* (they indicate the extent to which the goals DDOS, DAOS, DOI are achieved). |
| **Satisfy** | |
| ▪ The *system constraints* that must be satisfied for the solution to be feasible.<br>▪ There is no restriction placed on linearity or convexity.<br>$g_i(X) = 0;$ $i = 1,..., p$<br>$g_i(X) \geq 0;$ $i = p+1,...,p+q$<br>▪ The *system goals* that must achieve a specified target value as far as possible.<br>▪ There is no restriction placed on linearity or convexity. | ▪ Dynamic Desired Operability Space:<br>$\mathrm{DDOS} = \{(t_f, y_{sp}, d) \mid t_f \leq t_f^d(y_{sp}, d), \forall y_{sp} \in DOS, \forall d \in EDS\}$<br>▪ Dynamic Available Operating Spaces:<br>$DAOS = \{(t_f, y_{sp}, d) \mid t_f \geq t_f^*(y_{sp}, d), \forall y_{sp} \in DOS, \forall d \in EDS, u \in DAIS\}$<br>▪ Dynamic Operability Index:<br>$DOI = \frac{\mu[DDOS \cap DAOS]}{\mu[DOS \cup EDS]}$ |
| $A_i(X) + d_i^- - d_i^+ = G_i;$ $i = 1,..., m$<br>▪ The lower and upper *bounds* on the system.<br>$X_j^{min} \leq X_j \leq X_j^{max};$ $j = 1,..., n$<br>$d_i^-, d_i \geq 0$ and $d_i^- \cdot d_i^+ = 0$ | |
| **Minimize** | |
| The *deviation function* which is a measure of the deviation of the system performance from that implied by the set of goals and their associated priority levels or relative weights:<br>▪ Case a: Preemptive (lexicographic minimum)<br>$Z = [\, f_1(d_i^-, d_i^+), \ldots, f_k(d_i^-, d_i^+)\,]$<br>▪ Case b: Archimedean<br>$Z = \sum_{i=1}^{m} W_i(d_i^- + d_i^+);$<br>$\sum W_i = 1;\ W_i \geq 0.$ | The *deviation function* which is a measure of the deviation of the system performance from that implied by the set of goals (DDOS, DAOS, DOI) and their associated priority levels or relative weights. |

### 5.3.2 Dynamic Operability Analysis in Design for Dynamic Management. Different Scenarios

The test example considered to demonstrate the effectiveness of the Dynamic Operability Analysis method is the Continuously Stirred Tank Reactors.

***Continuously Stirred Tank Reactors.*** Interaction between design and control of single-CSTR and two-CSTRs-in-series systems with a first-order reaction of type A to B.

The two configurations have the same feed flow rates and conversion specifications. Schematics of these systems are shown in Figure 3.3. For a liquid-phase exothermic reaction taking place in a jacketed CSTR, the mass and energy balances can be written, with assumptions of constant physical properties and complete mixing. The model equations are made dimensionless with appropriate transformations and are presented in Appendix C.

Two scenarios for Continuously Stirred Tank Reactors are considered with same flow rates and conversion specifications:

1. Single Continuously Stirred Tank Reactor, see Figure 3.3, a); and
2. Two Continuously Stirred Tank Reactors, see Figure 3.3, b).

There are three design choices for Scenario 1. Design choice 1 (D1) where reactor temperature is 140[°F], design choice 2 (D2) where T = 160[°F], and design choice 3 (D3) where T = 180[°F], see Appendix C.

There are nine design choices for Scenario 2. Design choices 1 - 3 (D1-D3) where reactors volumes are the same and reactor temperatures are 140, 160, and 180[°F]. Design choices 4 - 6 (D4-D6) where reactors volumes ratio is 2 and reactor temperatures are140, 160, and 180[°F]. Design choices 7 - 9 (D7 - D9) where reactors volumes ratio is 0.5 and reactor temperatures are 140, 160, and 180[°F], see Appendix C.

For more information about the cSTR see Subramanian and co-authors **(**Subramanian, et al., 2001). The cDSP formulation of the Dynamic Operability Analysis of single-CSTR is presented in Appendix C.

The results from the SSOM, Section 5.4.1, and DOM, Section 5.4.2, are presented in and further discussed in Section 5.4.

## 5.4 Results and Discussion

In this section empirical performance validity of the Steady-State Operability Model (SSOM), Section 5.4.1, and the Dynamic Operability Model (DOM), Section 5.4.2, are presented. The usefulness of results are discussed in the end of this section.

### 5.4.1. Steady-State Operability Model Verification and Validation

The structure of the SSOM method is presented in Section 5.2, Figure 5.3, and in that order we present the results and discuss system operability. The SSOM method is illustrated using an example of automotive panel stamping process in three and four stations.

*Design of a Three Stage Panel Stamping Process*

***Servo Operability Index in the Output Space (SOIOS).*** In case of variant system design we want to see how much of desired output space (DOS) is achieved with available input space (AIS). The goal is maximize the Servo Operability Index in the Output Space (SOIOS). The SOIOS is full (equal to 1) if Available Output Space (AOS) and Desired Output Space (DOS) have identical spaces, i.e., if designer wishes match what system can deliver. If SOIOS is partial (less than 1) then redesign is required. System configuration obtained by exercising the ACRONES, Chapter 4, that reach full SOIOS for three stage panel stamping process with distributed, Figure 5.9, and end-of-line sensing configuration, Figure 5.10, are presented in Table 5.1.

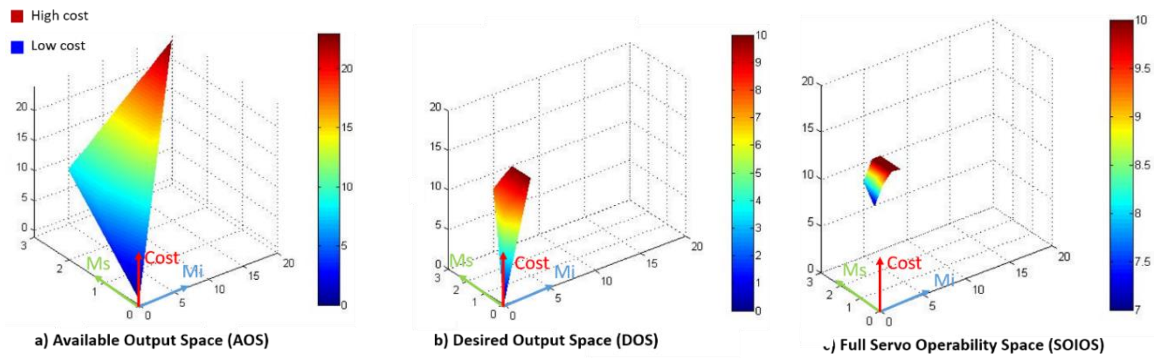



**Figure 5.9. Servo Operability Index in the Output Space (SOIOS) Solution Space for Distributes Sensing Configuration**

In design of the three stage panel stamping process with *distributed* and *end-of-line* sensing AOS is determined by exercising ACRONES and DOS is determined by designer wishes. It can be seen that DOS, see Figure 5.10, b), is much smaller than AOS, see Figure 5.10, a), since designer goal is to reduce the cost of the system. Full SOIOS, see Figure 5.10, c), is intersection between AOS and DOS. The solution space of full SOIOS is $7 \leq Cost \leq 10$, number of sensors $4 \leq M_i \leq 7$, and sensing stations $2 \leq M_S \leq 3$, see Table 5.1. The solution spaces of AOS and DOS are presented in Table 5.1.

**Table 5.1. Full Servo Operability Index in the Output Space (SOIOS) Solution Space**

| Sensing Configuration | Available Output Space | | | Desirable Output Space | | | Full Servo Operability Space | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mi [-] | Ms [-] | Cost [$] | Mi [-] | Ms [-] | Cost [$] | Mi [-] | Ms [-] | Cost [$] |
| **Distributed** | 4÷20 | 2÷3 | 7÷23 | 0÷7 | 0÷3 | 0÷10 | 4÷7 | 2÷3 | 7÷10 |
| **End-of-Line** | 0÷8 | 0÷1 | 3÷11 | 0÷2 | 0÷1 | 0÷5 | 0÷2 | 0÷1 | 3÷5 |

In design of the three stage panel stamping process with *end-of-line* sensing the cost of the process $3 \leq Cost \leq 5$, number of sensors $0 \leq M_i \leq 2$, and sensing stations $0 \leq M_S \leq 1$, see Table 5.1.

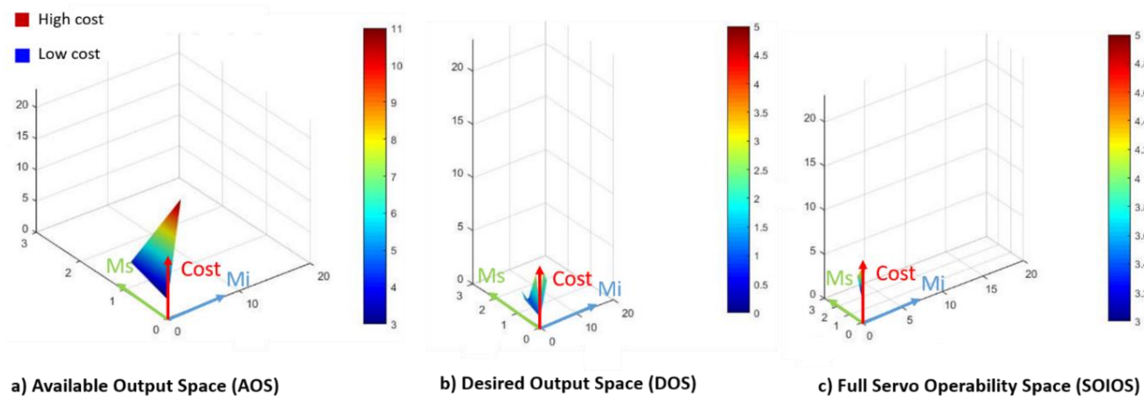
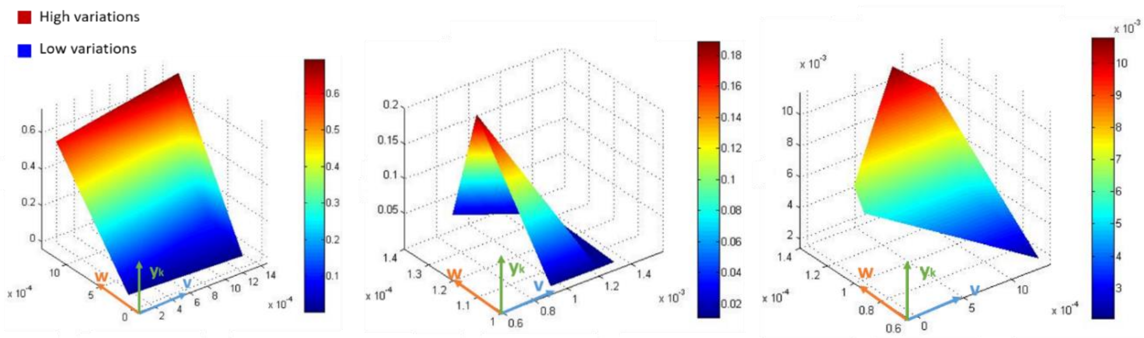



**Figure 5.10. Servo Operability Index in the Output Space (SOIOS) Solution Space for End-of-Line Sensing Configuration**

***Regulatory Operability Index (ROI).*** In case of variant system design determining the anticipated ranges of disturbances. The goal is to maximize the Regulatory Operability Index (ROI). The ROI is full (equal to 1) if Expected Disturbance Space (EDS) (natural uncertainty and model parameter uncertainty) in the system are within Tolerable Disturbance Space (TDS). If ROI is partial (less than 1) than redesign is required.

TDS is determined by designer experience of multistage system design recommendations where EDS is determined by exercising the ACRONES and full ROI is determined as intersection of EDS and TDS. In presence of natural uncertainty in design of panel stamping process with distributed sensing it can be seen that TDS, see Figure 5.11, a), is larger than EDS, see Figure 5.11, b), and full ROI, see Figure 5.11, c), is intersection between EDS and TDS.




a) Tolerable Disturbance Space (TDS) b) Expected Disturbance Space (EDS) c) Full Regulatory Operability Index (ROI)

**Figure 5.11. Regulatory Operability Index (ROI) Solution Space in the Presence of Natural Uncertainty for Distributes Sensing Configuration**

System configuration that reach full ROI for three stage panel stamping process with distributed and end-of-line sensing configuration in the presence of natural uncertainty are presented in Table 5.2.

**Table 5.2. Full Regulatory Operability Index (ROI) Solution Space for Natural Uncertainty**

| Sensing Configuration | i | Tolerable Disturbance Space | | | Expected Disturbance Space | | | Full Regulatory Operability Index | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $V$ [mm] | $W$ [mm] | $y_k$ [mm] | $V$ [mm] | $W$ [mm] | $y_k$ [mm] | $V$ [mm] | $W$ [mm] | $y_k$ [mm] |
| **Distributed** | 1 | 0.00124 | 0.00091 | 0.38600 | 0.00090 | 0.00010 | 0.01130 | 0.00090 | 0.00010 | 0.00563 |
| | 2 | 0.00000 | 0.00011 | 0.00682 | 0.00090 | 0.00013 | 0.18900 | 0.00000 | 0.00011 | 0.00682 |
| | 3 | 0.00147 | 0.00122 | 0.69300 | 0.00090 | 0.00014 | 0.02190 | 0.00090 | 0.00014 | 0.01080 |
| | 4 | 0.00103 | 0.00094 | 0.41200 | 0.00120 | 0.00010 | 0.01130 | 0.00103 | 0.00010 | 0.00563 |
| | 5 | 0.00003 | 0.00114 | 0.60600 | 0.00130 | 0.00010 | 0.01120 | 0.00003 | 0.00010 | 0.00565 |
| | 6 | 0.00126 | 0.00050 | 0.11700 | 0.00120 | 0.00013 | 0.01890 | 0.00120 | 0.00013 | 0.00938 |
| | 7 | 0.00131 | 0.00000 | 0.00206 | 0.00130 | 0.00014 | 0.02190 | 0.00130 | 0.00000 | 0.00206 |
| **End-of-Line** | 1 | 0.00121 | 0.00037 | 0.06705 | 0.00090 | 0.00010 | 0.00563 | 0.00090 | 0.00010 | 0.00563 |
| | 2 | 0.00114 | 0.00046 | 0.09705 | 0.00090 | 0.00013 | 0.00939 | 0.00090 | 0.00013 | 0.00939 |
| | 3 | 0.00144 | 0.00036 | 0.06178 | 0.00090 | 0.00014 | 0.01080 | 0.00090 | 0.00014 | 0.01080 |
| | 4 | 0.00135 | 0.00034 | 0.07603 | 0.00120 | 0.00010 | 0.00563 | 0.00103 | 0.00010 | 0.00563 |
| | 5 | 0.00127 | 0.00060 | 0.16670 | 0.00130 | 0.00010 | 0.00563 | 0.00130 | 0.00010 | 0.00563 |
| | 6 | 0.00116 | 0.00012 | 0.00821 | 0.00120 | 0.00013 | 0.00938 | 0.00120 | 0.00013 | 0.00938 |
| | 7 | 0.00138 | 0.00068 | 0.21492 | 0.00130 | 0.00014 | 0.01079 | 0.00130 | 0.00014 | 0.01079 |

In presence of natural uncertainty in design of panel stamping process with end-of-line sensing it can be seen that TDS, see Figure 5.11, a), is larger than EDS, see Figure 5.11, b), and full ROI, see Figure 5.11, c), is equal to EDS.

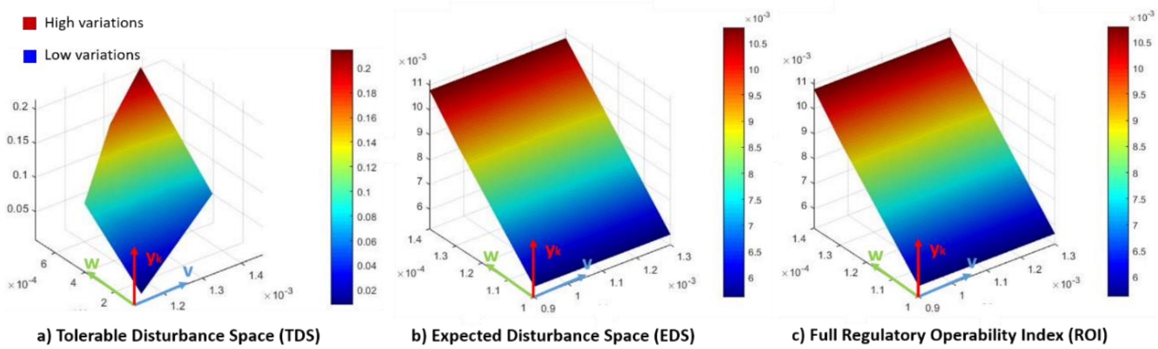



**Figure 5.12. Regulatory Operability Index (ROI) Solution Space in Presence of Natural Uncertainty for End-of-Line Sensing Configuration**

***Operability Index.*** Operability index provides us information whether system can regulate itself in the presence of disturbance (natural uncertainty) and is system functional in the presence of disturbance.

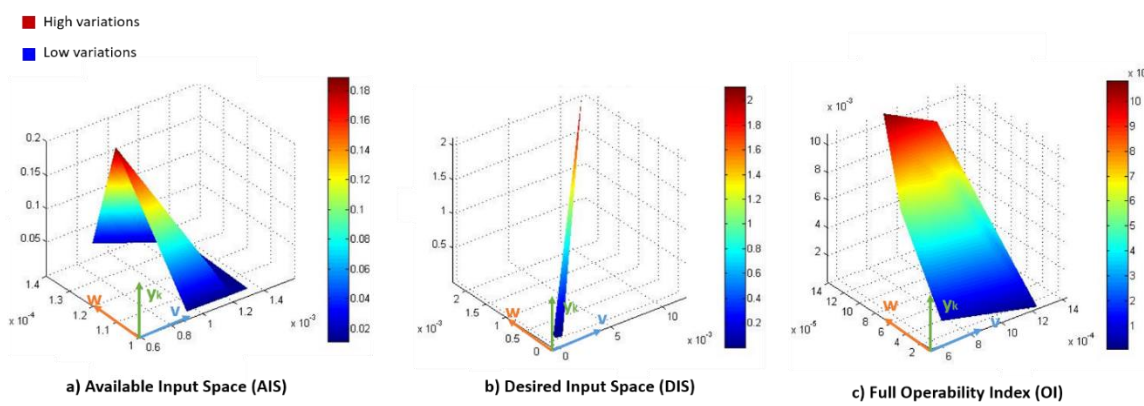



**Figure 5.13. Operability Index (OI) Solution Space in Presence of Natural Uncertainty for Distributes Sensing Configuration**

Available Input Space (AIS) is determined by exercising the ACRONES and Desired Input Space (DIS) is determined by designer wishes, experience or assumptions, where full operability of the system is intersection of AIS and DIS. In presence of disturbances (natural uncertainty) system is operable and its solution space is presented in Table 5.3.

In presence of natural uncertainty in design of panel stamping process with distributed sensing it can be seen that AIS, see Figure 5.13, a), is larger than DIS, see Figure 5.13, b), and full OI, see Figure 5.13, c), is intersection between AIS and DIS.

**Table 5.3. Full Operability Index (OI) Solution Space for Natural Uncertainty**

| Sensing Configuration | i | Available Input Space | | | Desired Input Space | | | Full Operability Index | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $V$ [mm] | $W$ [mm] | $y_k$ [mm] | $V$ [mm] | $W$ [mm] | $y_k$ [mm] | $V$ [mm] | $W$ [mm] | $y_k$ [mm] |
| **Distributed** | 1 | 0.00124 | 0.00091 | 0.14850 | 0.00232 | 0.00085 | 0.03501 | 0.00124 | 0.00085 | 0.33686 |
| | 2 | 0.00096 | 0.00041 | 0.20160 | 0.00198 | 0.00189 | 0.17000 | 0.00096 | 0.00041 | 0.07990 |
| | 3 | 0.00147 | 0.00122 | 0.13560 | 0.00143 | 0.00111 | 0.05928 | 0.00143 | 0.00111 | 0.57414 |
| | 4 | 0.00103 | 0.00094 | 0.17080 | 0.00346 | 0.00140 | 0.09394 | 0.00103 | 0.00094 | 0.41192 |
| | 5 | 0.00143 | 0.00114 | 0.34740 | 0.00229 | 0.00055 | 0.01445 | 0.00143 | 0.00054 | 0.13632 |
| | 6 | 0.00126 | 0.00050 | 0.01650 | 0.00116 | 0.00075 | 0.02668 | 0.00115 | 0.00050 | 0.11693 |
| | 7 | 0.00131 | 0.00062 | 0.44800 | 0.00054 | 0.00330 | 0.52085 | 0.00054 | 0.00062 | 0.17969 |
| **End-of-Line** | 1 | 0.00090 | 0.00010 | 0.00563 | 0.00232 | 0.00085 | 0.33996 | 0.00124 | 0.00085 | 0.33686 |
| | 2 | 0.00090 | 0.00013 | 0.00939 | 0.00198 | 0.00186 | 1.65396 | 0.00096 | 0.00041 | 0.07990 |
| | 3 | 0.00090 | 0.00014 | 0.01080 | 0.00143 | 0.00111 | 0.57668 | 0.00143 | 0.00111 | 0.57414 |
| | 4 | 0.00120 | 0.00010 | 0.00563 | 0.00346 | 0.00140 | 0.91224 | 0.00103 | 0.00094 | 0.41192 |
| | 5 | 0.00130 | 0.00010 | 0.00563 | 0.00229 | 0.00055 | 0.14032 | 0.00143 | 0.00054 | 0.13632 |
| | 6 | 0.00120 | 0.00013 | 0.00938 | 0.00116 | 0.00075 | 0.25964 | 0.00115 | 0.00050 | 0.11693 |
| | 7 | 0.00130 | 0.00014 | 0.01079 | 0.00054 | 0.00330 | 5.07071 | 0.00054 | 0.00062 | 0.17969 |

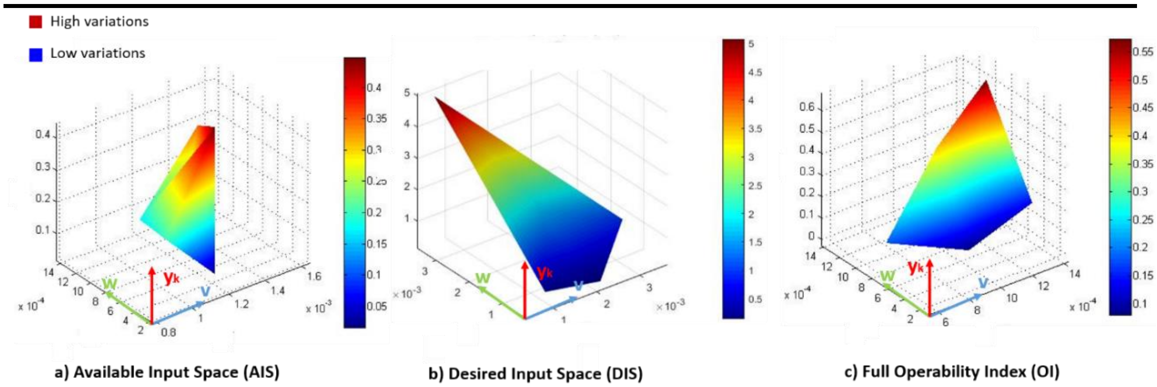



**Figure 5.14. Operability Index (OI) Solution Space in Presence of Natural Uncertainty for End-of-Line Sensing Configuration**

In presence of natural uncertainty in design of panel stamping process with end-of-line sensing it can be seen that AIS, see Figure 5.14, a), is larger than DIS, see Figure 5.14, b), and full OI, see Figure 5.14, c), is intersection between AIS and DIS.

***Servo Operability Index in the Output Space (SOIOS).*** Three attributes are observed in operating spaces for servo operability index in the output space, namely number of sensors, sensing stations, and related cost of the process. System configuration that reach full SOIOS for four stage panel stamping process with distributed, Figure 5.15, and end-of-line sensing configuration, Figure 5.16, are presented in Table 5.4.

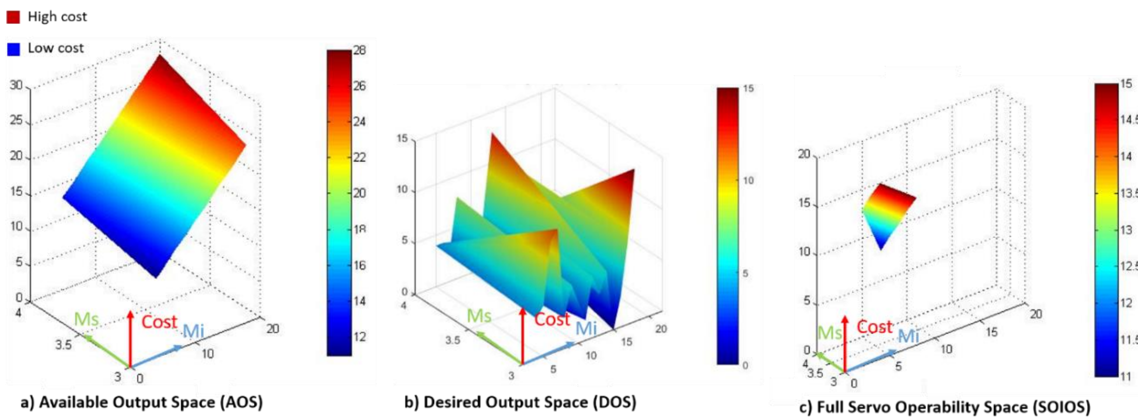



**Figure 5.15. Servo Operability Index in the Output Space (SOIOS) Solution Space for Distributes Sensing Configuration**

In case in design of the four stage panel stamping process with *distributed* sensing AOS, Figure 5.15, a), is larger than the DOS, Figure 5.15, b). Full servo operability of the system, Figure 5.15, c) is discovered as intersection between AOS and DOS.

In the AOS the available number of sensors is between 4 and 20, the available number of sensing stations is between 3 and 4, and cost of the system is between 11 and 27, see Table 5.4. In the DOS, desired number of sensors are between 0 and 15, desired number of sensing stations is between 0 and 4, and associated cost is between 0 and 15, see Table 5.4. The full SOIOS represent the intersection of these two spaces and it can be seen in Table 5.4 that number of sensors is between 4 and 15, number of sensing stations is between 3 and 4, and associated cost is between 11 and 15.

**Table 5.4. Full Servo Operability Index in the Output Space (SOIOS) Solution Space**

| Sensing Configuration | Available Output Space | | | Desirable Output Space | | | Full Servo Operability Space | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mi [-] | Ms [-] | Cost [$] | Mi [-] | Mi [-] | Ms [-] | Cost [$] | Ms [-] | Mi [-] |
| **Distributed** | 4÷20 | 3÷4 | 11÷27 | 0÷15 | 0÷4 | 0÷15 | 4÷15 | 3÷4 | 11÷15 |
| **End-of-Line** | 4÷6 | 1 | 7÷13 | 0÷5 | 0÷1 | 0÷10 | 5÷6 | 1 | 7÷10 |

In design of the four stage panel stamping process with *end-of-line* sensing if we want to cost of that design to be $7 \leq Cost \leq 10$ than system configurations with number of sensors from $0 \leq M_i \leq 3$ and sensing stations $0 \leq M_S \leq 1$, see Table 5.4.

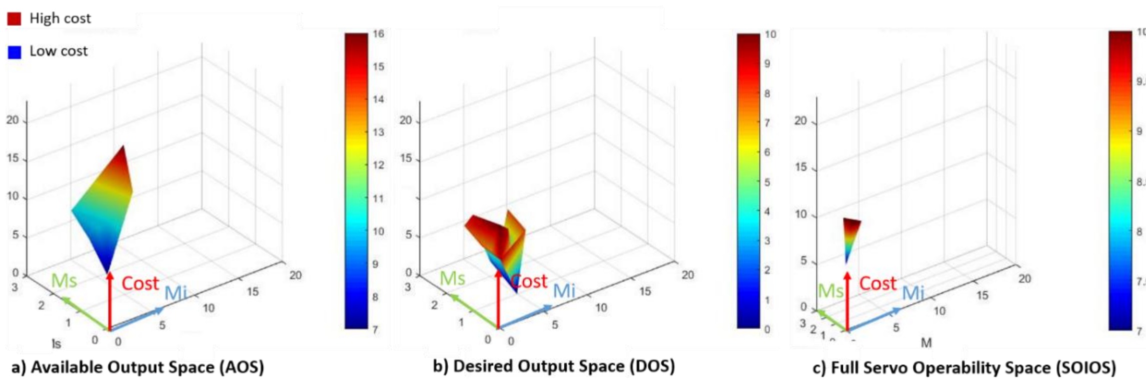
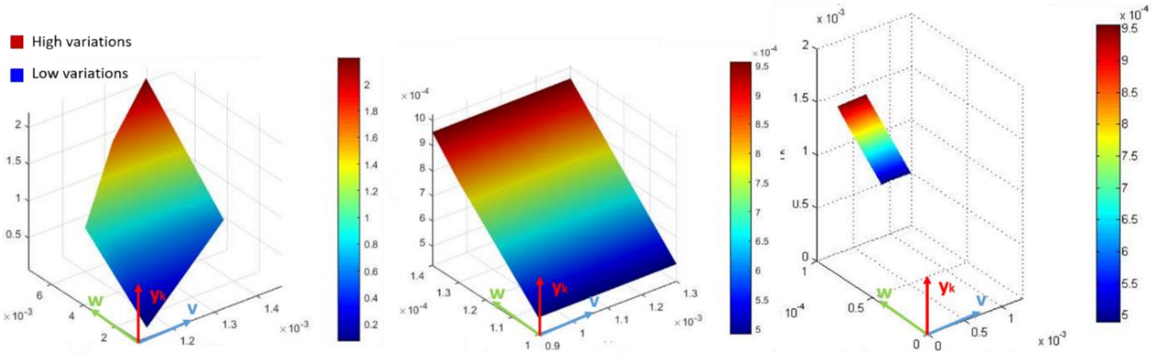



**Figure 5.16. Servo Operability Index in the Output Space (SOIOS) Solution Space for End-of-Line Sensing Configuration**

***Regulatory Operability Index (ROI).*** TDS is determined by designer experience of multistage system design recommendations where EDS is determined by exercising the ACRONES and full ROI is determined as intersection of these spaces.

In design of four stage panel stamping process with distributed sensing in presence of natural uncertainty it can be seen that TDS, see Figure 5.17, a), is larger than EDS, see Figure 5.17, b). Full ROI, see Figure 5.17, c), is found as intersection of TDS and EDS.




a) Tolerable Disturbance Space (TDS) b) Expected Disturbance Space (EDS) c) Full Regulatory Operability Index (ROI)

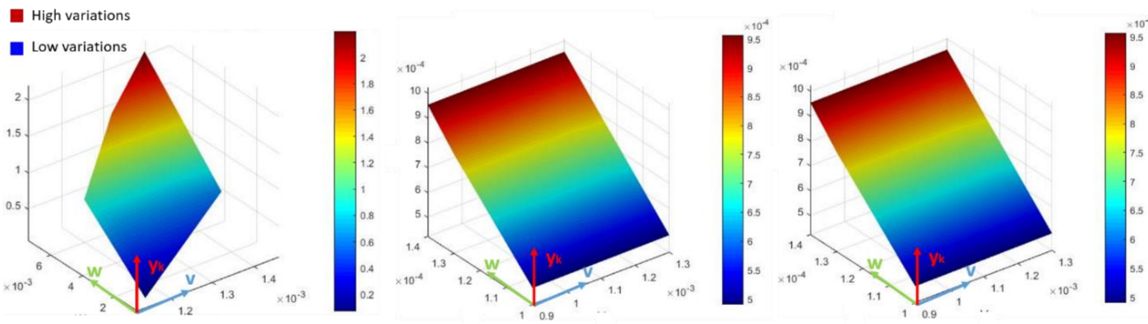
**Figure 5.17. Regulatory Operability Index (ROI) Solution Space in Presence of Natural Uncertainty for Distributes Sensing Configuration**

System configuration that reach full ROI for four stage panel stamping process with distributed and end-of-line sensing configuration in the presence of natural uncertainty are presented in Table 5.5.

**Table 5.5. Full Regulatory Operability Index (ROI) Solution Space for Natural Uncertainty**

| Sensing Configuration | i | Tolerable Disturbance Space | | | Expected Disturbance Space | | | Full Regulatory Operability Index | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $V$ [mm] | $W$ [mm] | $y_k$ [mm] | $V$ [mm] | $W$ [mm] | $V$ [mm] | $W$ [mm] | $y_k$ [mm] | $y_k$ [mm] |
| **Distributed** | 1 | 0.00121 | 0.00372 | 0.65992 | 0.00090 | 0.00010 | 0.00049 | 0.00090 | 0.00010 | 0.00049 |
| | 2 | 0.00114 | 0.00455 | 0.98834 | 0.00090 | 0.00013 | 0.00082 | 0.00090 | 0.00013 | 0.00082 |
| | 3 | 0.00144 | 0.00355 | 0.60259 | 0.00090 | 0.00014 | 0.00095 | 0.00090 | 0.00014 | 0.00095 |
| | 4 | 0.00135 | 0.00399 | 0.75948 | 0.00120 | 0.00010 | 0.00049 | 0.00103 | 0.00010 | 0.00049 |
| | 5 | 0.00127 | 0.00597 | 1.70455 | 0.00130 | 0.00010 | 0.00049 | 0.00130 | 0.00010 | 0.00049 |
| | 6 | 0.00116 | 0.00121 | 0.07047 | 0.00120 | 0.00013 | 0.00083 | 0.00120 | 0.00013 | 0.00083 |
| | 7 | 0.00138 | 0.00678 | 2.19876 | 0.00130 | 0.00014 | 0.00096 | 0.00130 | 0.00014 | 0.00096 |
| **End-of-Line** | 1 | 0.00121 | 0.00372 | 0.65992 | 0.00090 | 0.00010 | 0.00049 | 0.00090 | 0.00010 | 0.00049 |
| | 2 | 0.00114 | 0.00455 | 0.98834 | 0.00090 | 0.00013 | 0.000823 | 0.00090 | 0.00013 | 0.00082 |
| | 3 | 0.00144 | 0.00355 | 0.60259 | 0.00090 | 0.00014 | 0.000954 | 0.00090 | 0.00014 | 0.00095 |
| | 4 | 0.00135 | 0.00399 | 0.75948 | 0.00120 | 0.00010 | 0.000492 | 0.00103 | 0.00010 | 0.00049 |
| | 5 | 0.00127 | 0.00597 | 1.70455 | 0.00130 | 0.00010 | 0.000492 | 0.00130 | 0.00010 | 0.00049 |
| | 6 | 0.00116 | 0.00121 | 0.07047 | 0.00120 | 0.00013 | 0.000826 | 0.00120 | 0.00013 | 0.00083 |
| | 7 | 0.00138 | 0.00678 | 2.19876 | 0.00130 | 0.00014 | 0.000957 | 0.00130 | 0.00014 | 0.00096 |

The four stage panel stamping process with end-of-line sensing is designed in such way that sensor noise $V$ and process disturbances $W$ for combinations $i$ (i=1 – 7) of the EDS, Figure 5.18, b), are within the range of sensor noise $V$ and process disturbances $W$ of the TDS, Figure 5.18, a). In other words, EDS is a subspace of TDS. The ROI is same as EDS, Figure 5.18, c).




a) Tolerable Disturbance Space (TDS) b) Expected Disturbance Space (EDS) c) Full Regulatory Operability Index (ROI)

**Figure 5.18. Regulatory Operability Index (ROI) Solution Space in Presence of Natural Uncertainty for End-of-Line Sensing Configuration**

***Operability Index.*** Operability of variant design is examined discovering a region that intersects AIS and DIS. Desired Input Space (DIS) addressed here is necessary to reach all points in desired output space where value of output space is not at nominal value. Available Input Space (AIS) is inputs of the process able to change over a certain range. AIS are the input points available by exercising ACRONES or through prior designer knowledge, i.e., design experience.

AIS, Figure 5.19, a), is determined by exercising the ACRONES. DIS, Figure 5.19, b), is determined by designer wishes, experience or assumptions, and it is greater than AIS. Full operability of the system is found as intersection of AIS and DIS. In presence of disturbances (natural uncertainty) system is operable and its solution space is presented in Figure 5.19, c), and Table 5.6.

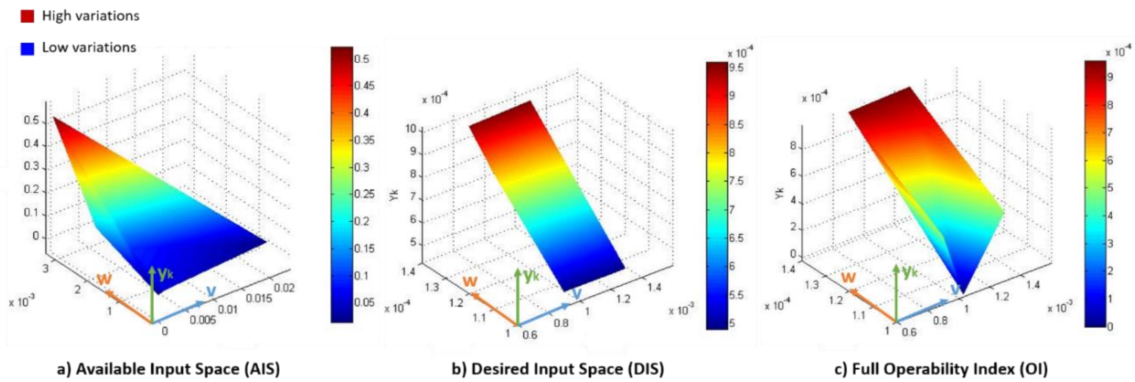



**Figure 5.19. Operability Index (OI) Solution Space in Presence of Natural Uncertainty for Distributes Sensing Configuration**

**Table 5.6. Full Operability Index (OI) Solution Space for Natural Uncertainty**

| Sensing Configuration | i | Available Input Space | | | Desired Input Space | | | Full Operability Index | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $V$ [mm] | $W$ [mm] | $y_k$ [mm] | $V$ [mm] | $W$ [mm] | $V$ [mm] | $W$ [mm] | $y_k$ [mm] | $y_k$ [mm] |
| **Distributed** | 1 | 9.51E-03 | 1.56E-03 | 1.17E-01 | 2.32E-03 | 8.50E-04 | 3.50E-02 | 2.32E-03 | 8.50E-04 | 3.47E-02 |
| | 2 | 8.62E-03 | 1.32E-03 | 8.39E-02 | 1.00E-05 | 1.88E-03 | 1.70E-01 | 1.00E-05 | 1.32E-03 | 8.33E-02 |
| | 3 | 6.23E-03 | 1.45E-03 | 1.01E-01 | 1.43E-03 | 1.00E-05 | 5.93E-02 | 1.43E-03 | 1.00E-05 | 0.00E+00 |
| | 4 | 1.22E-02 | 1.25E-03 | 7.55E-02 | 3.46E-03 | 1.40E-04 | 9.39E-02 | 3.46E-03 | 1.40E-04 | 7.50E-02 |
| | 5 | 1.33E-02 | 1.06E-02 | 5.35E+00 | 2.29E-02 | 5.50E-04 | 1.45E-02 | 1.33E-02 | 5.50E-04 | 1.49E-02 |
| | 6 | 1.22E-02 | 1.32E-03 | 8.42E-02 | 1.16E-03 | 1.40E-04 | 2.67E-02 | 1.16E-03 | 1.40E-04 | 9.50E-04 |
| | 7 | 1.39E-02 | 1.44E-02 | 9.85E-00 | 5.40E-04 | 3.30E-03 | 5.21E-01 | 5.40E-04 | 3.30E-03 | 5.21E-01 |
| **End-of-Line** | 1 | 9.51E-03 | 1.56E-03 | 1.17E-01 | 4.32E-03 | 8.50E-04 | 3.47E-02 | 4.32E-03 | 8.50E-04 | 3.48E-02 |
| | 2 | 8.62E-03 | 1.32E-03 | 8.39E-02 | 2.00E-05 | 1.88E-03 | 1.69E-01 | 2.00E-05 | 1.32E-03 | 8.33E-02 |
| | 3 | 6.23E-03 | 1.45E-03 | 1.01E-01 | 1.43E-03 | 1.11E-03 | 0.00E+00 | 1.43E-03 | 1.11E-03 | 2.90E-02 |
| | 4 | 1.22E-02 | 1.25E-03 | 7.55E-02 | 5.45E-03 | 1.00E-05 | 9.40E-02 | 5.45E-03 | 1.00E-05 | 0.00E+00 |
| | 5 | 1.33E-02 | 1.06E-02 | 5.35E+00 | 2.28E-03 | 5.40E-04 | 1.52E-02 | 2.28E-03 | 5.40E-04 | 1.40E-02 |
| | 6 | 1.22E-02 | 1.32E-03 | 8.42E-02 | 3.15E-03 | 7.40E-04 | 9.50E-04 | 3.15E-03 | 7.40E-04 | 2.63E-02 |
| | 7 | 1.39E-02 | 1.44E-02 | 9.85E-00 | 5.40E-04 | 3.00E-04 | 5.20E-01 | 5.40E-04 | 3.00E-04 | 4.33E-03 |

AIS, see Figure 5.20, a), is smaller than DIS, see Figure 5.20, b). Full operability of the system is found as intersection of AIS and DIS. In presence of disturbances (natural uncertainty) system is operable and its solution space is presented in Figure 5.20, c), and Table 5.6.

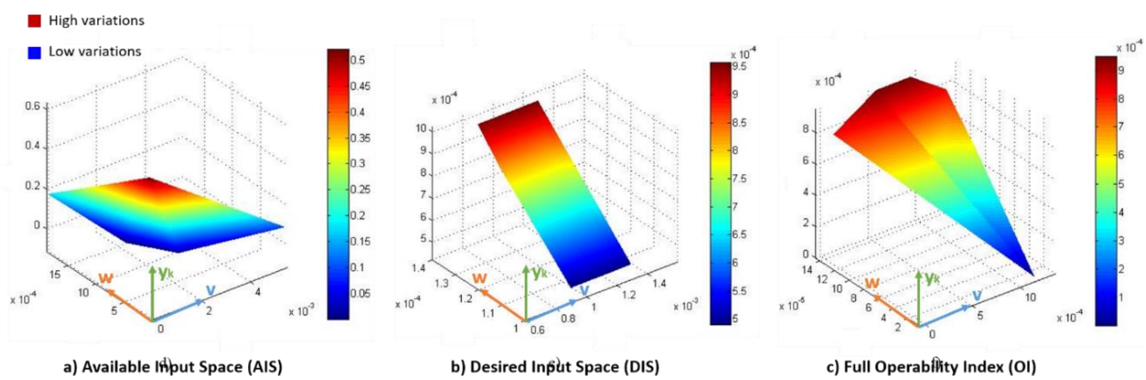



**Figure 5.20. Operability Index (OI) Solution Space in Presence of Natural Uncertainty for End-of-Line Sensing Configuration**

### 5.4.2. Dynamic Operability Model (DOM) Verification and Validation

The structure of the DOM method is presented in Section 5.3, Figure 5.8, and in that order we present the results and discuss system operability. The DOM method is illustrated using an example of continuous stirred tank rectors (CSTR) with single and two reactors.

*Design of a Single CSTR*

***Dynamic Desired Operating Space (DDOS).*** For desired Dynamic Available Input Space (DAIS) and Expected Disturbance Space (EDS), Desired Output Space (DOS) is achieved within desired response time, $t_f^d$. DAIS is design of CSTR is normalized volume of reactor, $V$, flow rate, $F$, and coolant flow rate $F_c$, Table 5.1. EDS is related to feed temperature, $T_0$, and feed flow rate, $F_0$, Table 5.1. DOS is related to exit concentration $C_A$ in single reactor, Table 5.1. DAIS and EDS information (range of inputs and rate of inputs change) are obtained by exercising the ACRONES and SSOM, Section 5.1. Desired response time to achieve DOS is obtained through min-time control calculus, see Appendix B. The goal is to achieve desired dynamic performance of a system within maximum allowable response time for three different designs Di (i=1, 2, 3). For more information about design choices in design of single-CSTR see Appendix C, Table C.1.

Dynamic desired operable space response within maximum allowable response time of 2 hours is presented in Table 5.7.

**Table 5.7. Dynamic Desired Output Space (DDOS) Time Output Response of a Single-CSTR Design**

| Design | Dynamic Available Input Space | | | Desired Output Space | Expected Disturbance Space | | |
|---|---|---|---|---|---|---|---|
| | $\frac{V}{V^R}$ [-] | $\frac{F}{F^R}$ [-] | $\frac{F_C}{F_C^R}$ [-] | $C_A$ $[\mathrm{lbmol\ ft^{-3}}]$ | $T_0$ [°F] | $F_0$ $[\mathrm{ft^3 h^{-1}}]$ | $t_f^d$ [h] |
| **Di** | 0.3÷1.0 | 0.5÷1.5 | 0÷4 | 0.02÷0.2 | 50÷90 | 50÷150 | 0÷2 |

***Dynamic Achievable Operating Space (DAOS).*** For a given choice of DAIS and EDS, DOS is achieved in respect to minimum response time, $t_f^*$. The goal is to achieve dynamic performance of a system within minimum allowable performance time for all three designs Di (i=1, 2, 3). Dynamic achievable operable space response within minimum allowable response time of 1 hour is presented in Table 5.8.

**Table 5.8. Dynamic Available Output Space (DAOS) Time Output Response of a Single-CSTR Design**

| Design | Dynamic Available Input Space | | | Desired Output Space | Expected Disturbance Space | | |
|---|---|---|---|---|---|---|---|
| | $\frac{V}{V^R}$ [-] | $\frac{F}{F^R}$ [-] | $\frac{F_C}{F_C^R}$ [-] | $C_A$ $[\mathrm{lbmol\ ft^{-3}}]$ | $T_0$ [°F] | $F_0$ $[\mathrm{ft^3 h^{-1}}]$ | $t_f^*$ [h] |
| **D1** | 0.3 | 0.976÷1.246 | 1÷1.510 | 0.02÷0.039 | 49.5÷70 | 99.75÷100 | 0÷1 |
| **D2** | 0.2 | 0.7÷1.3 | 0.5÷1.5 | ~0.02 | ~70 | ~100 | 0÷0.004 |
| **D3** | 0.0 | 0.8÷1.3 | 0.0÷0.42 | 0.02÷0.0204 | 62.91÷70 | ~100 | 0÷0.014 |

***Dynamic Operability Index (DOI).*** The DOI is calculated from min-time plots. If desired response time is $t_f^d = 0.01\ [h]$, horizontal green dashed line in Figure 22, to reach all $y_{sp}$ in DOS than it can be seen that D1 reached DOI of 30%, D2 of 60%, and D3 of ~100%.

The minimum transition time that are needed for moving reactor from concentration of 0.02 [lbmol ft$^{-3}$] to nominal concentration of 0.05 [lbmol ft$^{-3}$] are calculated for D1-D3 and presented in Figure 5.21. The results of three different design of single CSTR are compared in Figure 5.21. It can be seen that reactor D3 transits faster than D2 and D1. However, reactor D1 transit slower and steady toward nominal concentration, $C_A$, than reactors D2 and D3.

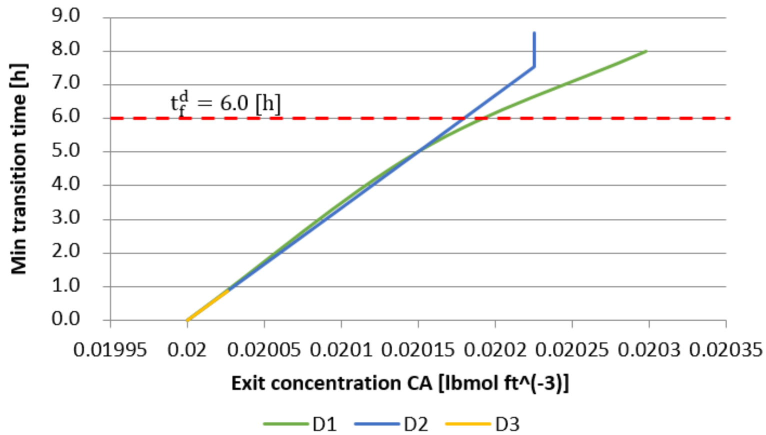



**Figure 5.21. Minimum-Transition Time for Single CSTR Designs**

The minimum-disturbance rejection time calculations in the feed flow rate for D1-3 are presented in Figure 5.22. It can be seen that reactor D3 reject disturbances faster than D1 and D2. Based on minimum transition and rejection time it can be concluded that design D3 gives us better results than D2 and D1.

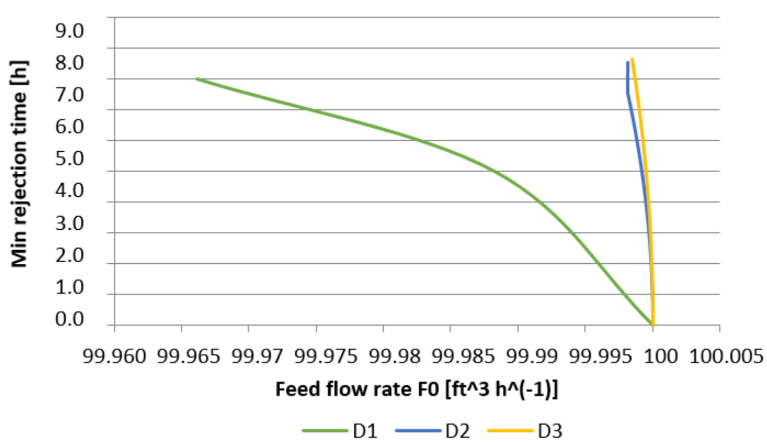



**Figure 5.22. Minimum-Disturbance Rejection Time for Single CSTR Designs**

*Design of Two-CSTR*

***Dynamic Desired Operating Space (DDOS).*** For desired Dynamic Available Input Space (DAIS) and Expected Disturbance Space (EDS), Desired Output Space

(DOS) is achieved within desired response time, $t_f^d$. DAIS is design of cSTR is normalized volume of Reactors 1 and 2, $V_i$, flow rate, $F_i$, and coolant flow rate $F_{ci}$, Appendix C, Table C.8. EDS is related to feed temperature, $T_0$, and feed flow rate, $F_0$, Appendix C, Table C.8. DOS is related to exit concentration $C_A$ of Reactors 1 and 2, Appendix C, Table C.8. The goal is to achieve desired dynamic performance of a system within maximum allowable response time for different designs Di (i=1,…, 9). Design alternatives in design of two-CSTR are presented in Appendix C, Table C.8. Dynamic desired operable space response within maximum allowable response time of 2 hours is presented in Table 5.9.

**Table 5.9. Dynamic Desired Output Space (DDOS) Time Output Response of Two-CSTR Design with Volume Ration of 1.0, 2.0, and 0.5**

| Design | Dynamic Available Input Space | | | | | | Desired Output Space | | Expected Disturbance Space | | $t_f^*$ [h] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\frac{V_1}{V_1^R}$ [ft³] | $\frac{V_2}{V_2^R}$ [ft³] | $\frac{F_1}{F_1^R}$ [ft³h⁻¹] | $\frac{F_2}{F_2^R}$ [ft³h⁻¹] | $\frac{F_{c1}}{F_{c1}^R}$ [ft³h⁻¹] | $\frac{F_{c2}}{F_{c2}^R}$ [ft³h⁻¹] | $C_{A1}$ [lbmol ft⁻³] | $C_{A2}$ [lbmol ft⁻³] | $T_0$ [°F] | $F_0$ [ft³h⁻¹] | |
| $D_i$ | 0.3÷1.0 | 0.3÷1.0 | 0.5÷1.5 | 0.5÷1.5 | 0.0÷4.0 | 0.0÷4.0 | 0.02÷0.2 | 0.02÷0.2 | 50÷90 | 50÷150 | 0.0÷2.0 |

***Dynamic Achievable Operating Space (DAOS).*** For a given choice of DAIS and EDS, DOS is achieved in respect to minimum response time, $t_f^*$. The goal is to achieve dynamic performance of a system within minimum allowable performance time. Dynamic achievable operable space response within minimum allowable response time of 1 hour is presented in Table 5.10.

**Table 5.10, a. Dynamic Available Output Space (DAOS) Time Output Response of Two-CSTR Design with Volume Ration of 1.0**

| Design | Dynamic Available Input Space | | | | | | Desired Output Space | | Expected Disturbance Space | | $t_f^*$ [h] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $V_1$ [ft³] | $V_2$ [ft³] | $F_1$ [ft³h⁻¹] | $F_2$ [ft³h⁻¹] | $F_{c1}$ [ft³h⁻¹] | $F_{c2}$ [ft³h⁻¹] | $C_{A1}$ [lbmol ft⁻³] | $C_{A2}$ [lbmol ft⁻³] | $T_0$ [°F] | $F_0$ [ft³h⁻¹] | |
| **D1** | 400÷651 | 208÷400 | ~100 | ~80 | 70÷99 | 61÷63 | 0.02÷0.2 | 0.02÷0.19 | ~70 | ~100 | 0÷0.92 |
| **D2** | 200÷352 | 136÷200 | ~100 | ~80 | 70÷108 | 70÷108 | ~0.02 | ~0.02 | ~70 | ~100 | 0÷1 |
| **D3** | 200÷295 | 88÷200 | ~100 | ~80 | 70÷108 | 18÷78 | ~0.02 | 0.02÷0.2 | ~70 | ~100 | 0÷1 |
| **D4** | 200÷352 | 148÷200 | ~100 | ~80 | 70÷112 | 0÷20 | ~0.02 | 0.02÷0.2 | ~70 | ~100 | 0÷1 |
| **D5** | 200÷304 | 93÷200 | ~100 | ~80 | 70÷112 | 0÷20 | ~0.02 | 0.02÷0.2 | ~70 | ~100 | 0÷1 |
| **D6** | 200÷208 | 62÷200 | ~100 | ~80 | 70÷87 | 6÷30 | ~0.02 | 0.02÷0.2 | ~70 | ~100 | 0÷1 |
| **D7** | 200÷295 | 88÷200 | ~100 | ~80 | 70÷87 | 6÷30 | ~0.02 | 0.02÷0.2 | ~70 | ~100 | 0÷1 |
| **D8** | 200÷208 | 62÷200 | ~100 | ~80 | 70÷87 | 6÷30 | ~0.02 | 0.02÷0.2 | ~70 | ~100 | 0÷1 |
| **D9** | 144 | 43÷145 | ~100 | ~80 | 70÷87 | 0÷20 | ~0.02 | 0.02÷0.2 | ~70 | ~100 | 0÷1 |

**Table 5.10, b. Dynamic Available Output Space (DAOS) Time Output Response of Two-CSTR Design with Volume Ration of 2.0**

| Design | Dynamic Available Input Space | | | | | | Desired Output Space | | Expected Disturbance Space | | $t_f^*$ [h] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $V_1$ [ft³] | $V_2$ [ft³] | $F_1$ [ft³h⁻¹] | $F_2$ [ft³h⁻¹] | $F_{c1}$ [ft³h⁻¹] | $F_{c2}$ [ft³h⁻¹] | $C_{A1}$ [lbmol ft⁻³] | $C_{A2}$ [lbmol ft⁻³] | $T_0$ [°F] | $F_0$ [ft³h⁻¹] | |
| **D1** | 400÷485 | 291÷700 | ~50 | ~100 | 70÷86 | 68÷70 | 0.02÷0.07 | 0.05÷0.2 | 69÷70 | ~100 | 0.0÷0.5 |
| **D2** | 300÷307 | 184÷600 | 50÷51 | ~80 | 70÷85 | 68÷70 | 0.02÷0.1 | 0.05÷0.2 | ~70 | ~100 | 0.0÷0.7 |
| **D3** | 140÷192 | 114÷280 | 50÷51 | ~100 | 160÷170 | 76÷80 | ~0.02 | 0.05÷0.2 | ~90 | ~100 | 0.0÷1.0 |
| **D4** | 200÷328 | 196÷400 | 50÷51 | ~100 | 140÷164 | 65÷69 | ~0.02 | 0.05÷0.2 | ~70 | ~100 | 0.0÷1.0 |
| **D5** | 203÷215 | 151÷405 | 58÷59 | ~108 | 191÷204 | 59÷62 | 0.02÷0.15 | 0.05÷0.2 | ~73 | ~108 | 0.0÷0.5 |
| **D6** | 120÷141 | 84÷240 | ~50 | ~100 | 160÷176 | 31÷40 | 0.05÷0.15 | 0.05÷0.2 | ~70 | ~100 | 0.0÷0.5 |
| **D7** | 203÷215 | 151÷405 | 58÷59 | ~108 | 191÷204 | 59÷62 | 0.02÷0.15 | 0.05÷0.2 | ~73 | ~108 | 0.0÷0.5 |
| **D8** | 141÷149 | 97÷282 | 54÷55 | ~104 | 157÷171 | 45÷51 | 0.02÷0.2 | 0.05÷0.2 | ~72 | ~104 | 0.0÷0.5 |
| **D9** | 101 | 62÷202 | 51÷52 | ~101 | 123÷133 | 56÷60 | ~0.02 | 0.05÷0.2 | ~71 | ~101 | 0.0÷1.0 |

**Table 5.10, c. Dynamic Available Output Space (DAOS) Time Output Response of Two-CSTR Design with Volume Ration of 0.5**

| Design | Dynamic Available Input Space | | | | | | Desired Output Space | | Expected Disturbance Space | | $t_f^*$ [h] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $V_1$ [ft³] | $V_2$ [ft³] | $F_1$ [ft³h⁻¹] | $F_2$ [ft³h⁻¹] | $F_{c1}$ [ft³h⁻¹] | $F_{c2}$ [ft³h⁻¹] | $C_{A1}$ [lbmol ft⁻³] | $C_{A2}$ [lbmol ft⁻³] | $T_0$ [°F] | $F_0$ [ft³h⁻¹] | |
| **D1** | 289÷400 | 231÷485 | ~50 | ~100 | 70÷188 | 44 | 0.19÷0.2 | 0.05÷0.2 | ~70 | ~100 | 0.0÷0.65 |
| **D2** | 289÷400 | 231÷485 | ~50 | ~100 | 70÷188 | 44 | 0.19÷0.2 | 0.05÷0.2 | ~70 | ~100 | 0.0÷0.65 |
| **D3** | 135÷206 | 106÷220 | ~51 | ~101 | 202÷287 | 35÷40 | 0.02÷0.1 | 0.05÷0.2 | ~71 | ~101 | 0.0÷1.0 |
| **D4** | 184÷320 | 187÷307 | ~50 | ~100 | 200÷262 | 27÷30 | 0.02÷0.1 | 0.05÷0.2 | ~70 | ~100 | 0.0÷1.0 |
| **D5** | 129÷200 | 103÷215 | ~50 | ~100 | 240÷261 | 25÷30 | 0.02÷0.1 | 0.05÷0.2 | ~70 | ~100 | 0.0÷1.0 |
| **D6** | 97÷152 | 58÷150 | ~54 | 103÷104 | 130÷256 | 24÷31 | 0.02÷0.1 | 0.05÷0.2 | ~72 | ~104 | 0.0÷1.0 |
| **D7** | 115÷150 | 62÷192 | ~50 | 99÷100 | 160÷223 | 12÷20 | 0.02÷0.1 | 0.05÷0.2 | ~72 | ~104 | 0.0÷1.0 |
| **D8** | 91÷152 | 58÷141 | ~54 | 103÷104 | 129÷229 | 12÷21 | 0.02÷0.1 | 0.05÷0.2 | ~72 | ~104 | 0.0÷1.0 |
| **D9** | 60÷100 | 30÷101 | ~50 | 99÷100 | 120÷232 | 9÷20 | 0.02÷0.1 | 0.05÷0.2 | ~70 | ~100 | 0.0÷1.0 |

***Dynamic Operability Index (DOI).*** The DOI is calculated from min-time plots. We presented results from representative designs $D_i$ for different volumes ratio, $R_v$, Figure 5.23. If desired response time is $t_f^d = 0.6\ [h]$, horizontal green dashed line in Figure 5.23, to reach all $y_{sp}$ in DOS than D8 for Rv=1.0 has DOI of 100%, D3 for Rv = 2.0 has DOI of 100%, and D9 for Rv=0.5 has DOI of 100%.

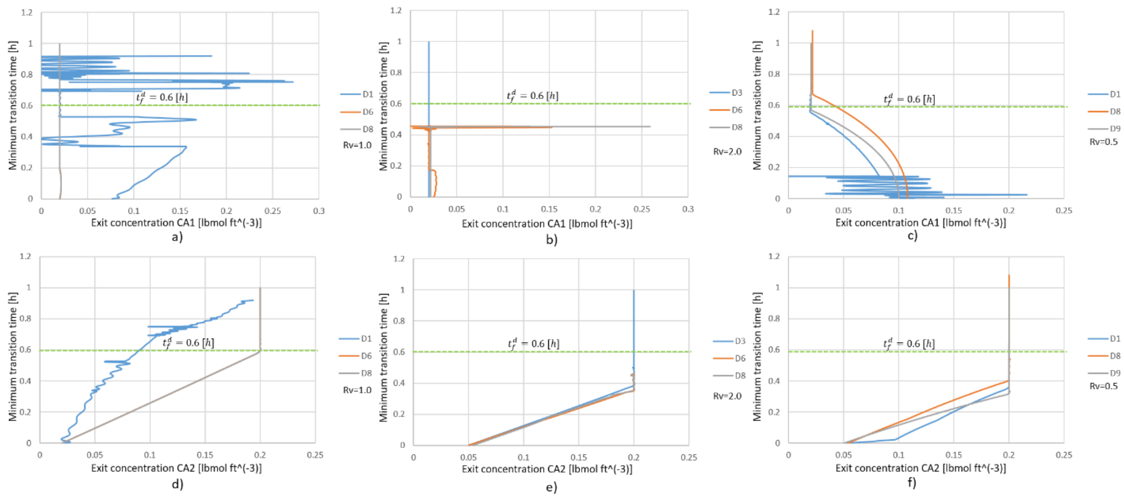


**Figure 5.23. Minimum-Transition Time for Two-CSTR Selected Designs**

The minimum transition time that are needed for moving reactor from concentration of 0.02 [lbmol ft$^{-3}$] to nominal concentration of 0.2 [lbmol ft$^{-3}$] are calculated for D1-D9 for different $R_v$ and presented in Figure 5.23. The results of representative different design of two-CSTR are compared in Figure 5.23. It can be seen that reactor D8 transits faster than D1 and D6 for Rv=1.0. Reactor D3 transits faster than D6 and D8 for Rv=2.0. Lastly, reactor D9 transits faster than D1 and D8 for Rv=0.5. The minimum-disturbance rejection time calculations in the feed flow rate for D1-9 for different Rv are presented in Figure 5.24. It can be seen that Reactor D8 reject disturbances faster than D1 and D6 for Rv=1.0. Further, Reactors D3, D6, D8 reject disturbances with same pace for Rv=2.0. Lastly, Reactor D9 reject disturbances faster than D1 and D8 for Rv=0.5.

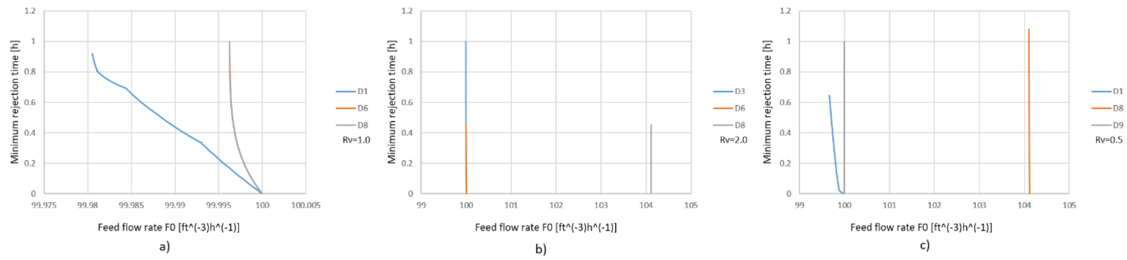



**Figure 5.24. Minimum-Disturbance Rejection Time for Two-CSTR Selected Designs.**

## 5.5 Synopsis of Chapter 5

In this chapter, Empirical Structural and Performance Validity of the Research Question 2 "*What is the computational framework in the design method that facilitates dynamic change in the requirements in realization of functional networked engineering systems?*" is addressed. The answer is the method for operability analysis, Section 5.1. The empirical structural validity of the method, Quadrant 2 of the Validation Square, is presented in Sections 5.2 and 5.3. The empirical performance validity of the method, Quadrant 3 of the Validation Square, is presented in Section 5.4.

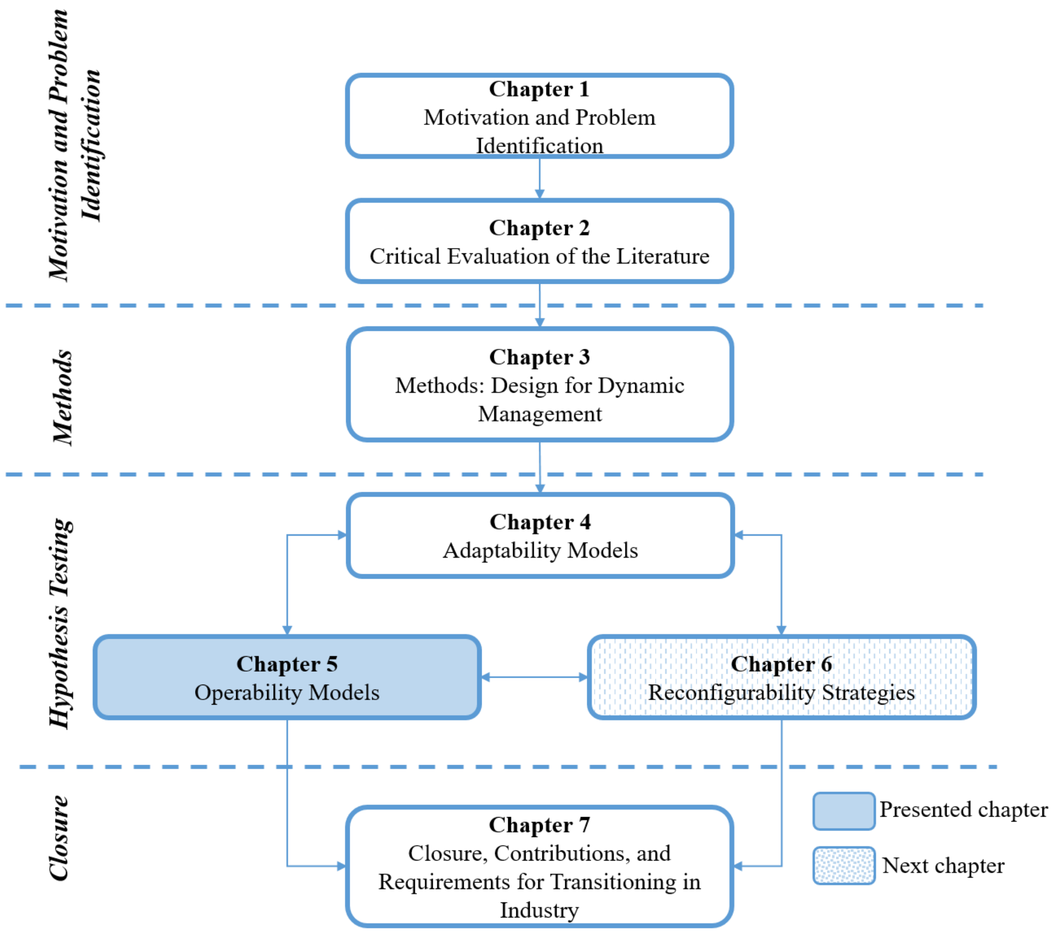



**Figure 5.25. Organization of the Dissertation – Presented and Next Chapter**

In next chapter, Figure 5.25, third part of the problem, Chapter 3, Section 3.1, is addressed regarding system reconfigurability. The strategy for Reconfigurable Machine Tool (RMT), Section 6.1, Reconfigurable Inspection System (RIS), Section 6.2, and Reconfigurable Manufacturing System (RMS), Section 6.3, is presented.

# CHAPTER 6

# REALIZATION OF DYNAMIC MANAGEMENT IN RECONFIGURABLE MANUFACTURING SYSTEM

In this chapter, a model-based exploration method for reconfiguration strategy of Reconfigurable Manufacturing System (RMS) is presented as answer to the second part of the problem in design of networked engineering systems, determining reconfiguration strategies allow multiple configurations of elements in the system, is presented an answer to the Research Question 3 introduced in Chapter 1, Section 1.4, and justified through critical literature review in Chapter 2, Section 2.3. The reconfigurability problem in the design of networked engineering systems is introduced in Chapter 3, Section 3.1. The reconfiguration strategy method is a component of the computational framework, *Design for Dynamic Management,* presented as highlighted quadrant in Figure 6.1. Further, three different issues are addressed in the reconfiguration strategy (1) model the performance of RMTs layout (i.e. capacity), and discuss the reconfiguration design of RMT layout in the compromise Decision Support Problem (cDSP) construct; (2) model the performance of RITs distribution (i.e. diagnosability), and discuss the reconfiguration design of RIT distribution in the cDSP construct; and (3) integrate multiple cDSPs to explore RMS reconfiguration strategy regarding to the systemic goals (i.e. investment, flexibility).

In Section 6.1, the Reconfigurable Machine Tool (RMT) model is presented. In Section 6.2, the Reconfigurable Inspection System (RIS) model is presented. In Section 6.3, the Reconfigurable Manufacturing System (RMS) model is presented. In Section 6.4, results and discussion of the models is discussed. Lastly, summary of Chapter 6 is presented in Section 6.5.

***Chapter 6 is written in collaboration with MS Xiwen Shang from Beijing Institute of Technology in China and under mentorship of Dr. Janet K. Allen, Dr. Guoxin Wang, and Dr. Farrokh Mistree.***

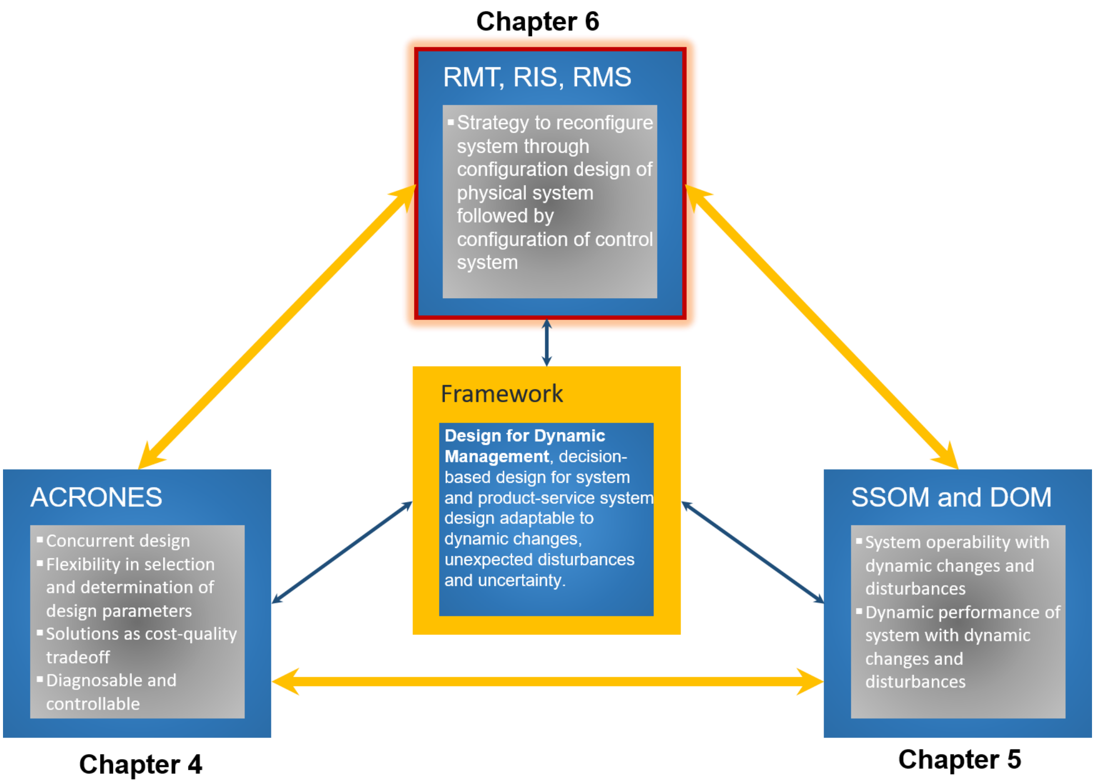



**Figure 6.1. Reconfiguration Strategy in Design for Dynamic Management**

## 6.1 Reconfigurable Machine Tool (RMT) Design in Dynamic Management

In this section development of Reconfigurable Machine Tool (RMT) configuration design is presented. First step, Section 6.2.2, is construction of the configuration tree. Second step, Section 6.2.3, is construction of the constraint model. Last step, Section 6.2.4, is the construction of the objective model.

### 6.1.1 Development of RMT Configuration Design

Current design research on Reconfigurable Manufacturing Tool (RMT) is based on modularization theory. Further, there is a need for RMT design development regarding geometry, size, accuracy and other parameters (Koren, et al., 1999; Son, et al., 2010; Padayachee, et al., 2009). Therefore, diverse modules for RMT configuration design is developed. As a result, an enterprise has individual module libraries to support the design, which are not necessarily available to other enterprises. RMT configurations can be generated by different enterprises from different module libraries, Figure 6.2. Consequently, modules from different libraries have different parameters (e.g., geometry), and language to describe two different configurations concurrently in the design process is quite complex.

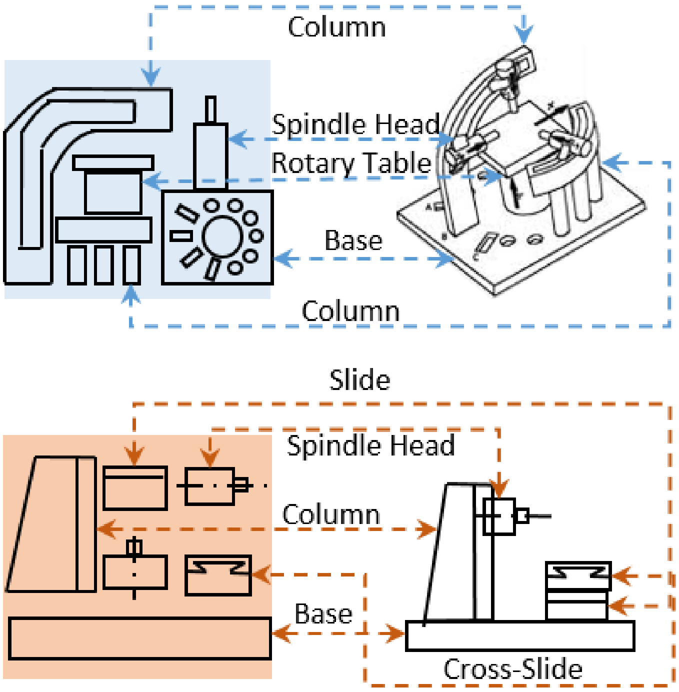



**Figure 6.2. RMT Configuration Design from Different Module Libraries**

The challenge of complexity in describing two different configurations concurrently in the design process can be overcome by explaining how to carry out the process of design using critical indices and developing a common method for the description of the configuration (Roozenburg and Eekels, 1995). First step is to develop a common model and make the design method more comprehensive and practical for use with different module libraries. The most important part of the common design method is the process of mapping, Figure 6.3.

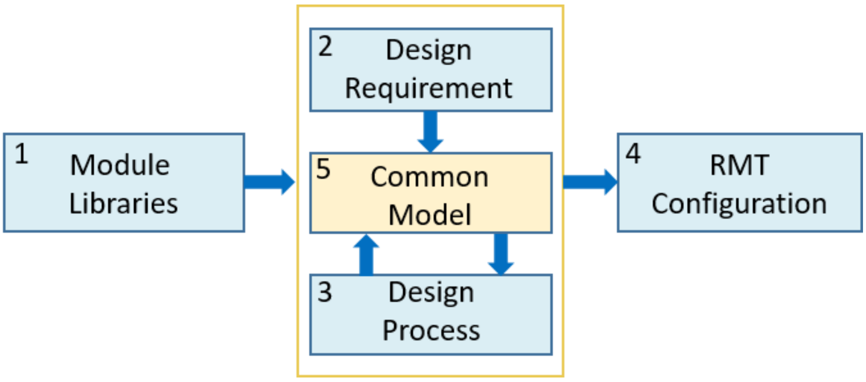



**Figure 6.3. Schematic of the Design with the Common Mode**

Common mode has five blocks, Figure 6.3, design requirement, module libraries, common model, design process, and RMT configuration. The first block is the specified module library mapped into the common model. The second block is based on the design requirement, the common model is used to design a RMT. The third block is the solution of the design process obtained and expressed with a common model. The fourth block is the RMT design in the common model mapped into an RMT configuration with the required module library.

To ensure that the method can work for any module library, we introduce the concept of a configuration tree as a common model (Wang, et al., 2017). A configuration tree is a functional model to describe RMT configuration based on a tree structure diagram. The tree structure diagram is a data structure made up of finite nodes and edges, as in graph theory. In a tree, the nodes are hierarchically arranged by edges. An RMT design configuration consists of modules, which are integrated into an assembly relationship. Due to the similar structures of the tree and RMT configuration, RMT configurations are developed in the form of a tree. When decomposing an RMT structural configuration, the hierarchy of the design process from the most general to the most specific progresses from configuration to tool-related configuration combined with workpiece-related configuration and modules. Tool-related configuration is used to achieve the motion of the tool, while the workpiece-related configuration is the motion of workpiece which must also be configured. Therefore, each node in the configuration tree represents a module in the RMT configuration. An edge indicates a parent-child relationship between nodes and thereby represents the assembly relationship among the modules.

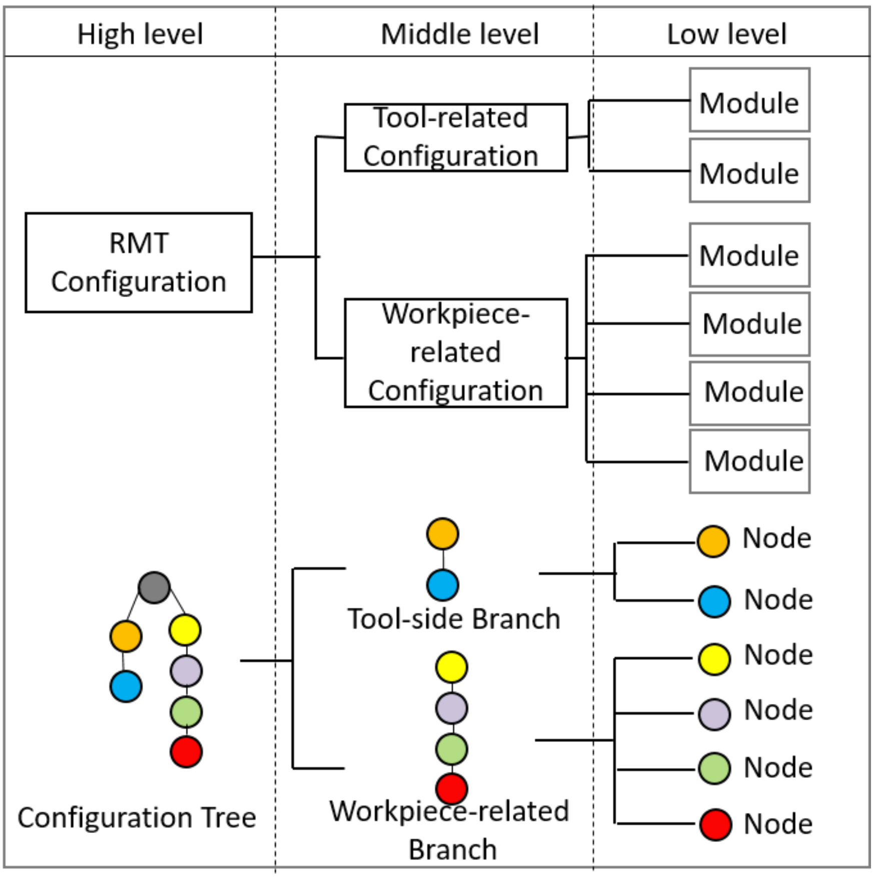



**Figure 6.4. Mapping Relationship RMT Configuration and Configuration Tree**

The branches are subsets of nodes and edges in the configuration tree, and they represent sub-configurations. The branch with the tool-related configurations is called tool-side branch, and the branch with the workpiece-related configurations is called the workpiece-side branch. Thus, the configuration tree diagram is used to represent the entire RMT configuration. The mapping relationship between the RMT configuration and the configuration tree is shown in Figure 6.4.

Given a function, the mapping from RMT configuration to configuration tree is one-to-one. Therefore, the configuration tree can be used to describe an RMT configuration design with various module libraries. Furthermore, using a configuration tree, it is possible to partially automate an RMT design process based on its data structure. The proposed RMT configuration design method includes three stages: configuration description, configuration formation, and configuration evaluation, Figure 6.5.

- ***Configuration description, Block A, Figure 6.5.*** This step is the foundation of the proposed design method, which is supported by mapping between the RMT configuration and the configuration tree. Step A1, the RMT configuration is mapped into the tree, and the configuration design variables are defined by the node and edge sets. After selecting the most satisfactory configuration tree scheme, the module and assembly relationships can be determined by the node, Step A2, and the edge sets and thus the RMT configuration design is formed, Step A3.
- ***Configuration generation, Block B, Figure 6.5.*** This step is the core of the design method, which is supported by the constraint model of the required capability and functionality. These models help to make decisions on node sets from the node library. The node set is used to satisfy the requirement of customized capability, and then the proper node set is used to generate feasible configuration trees. At this stage, adding, removing, or moving nodes in the configuration tree is used to represent the reconfiguration of modules in the RMT configuration.

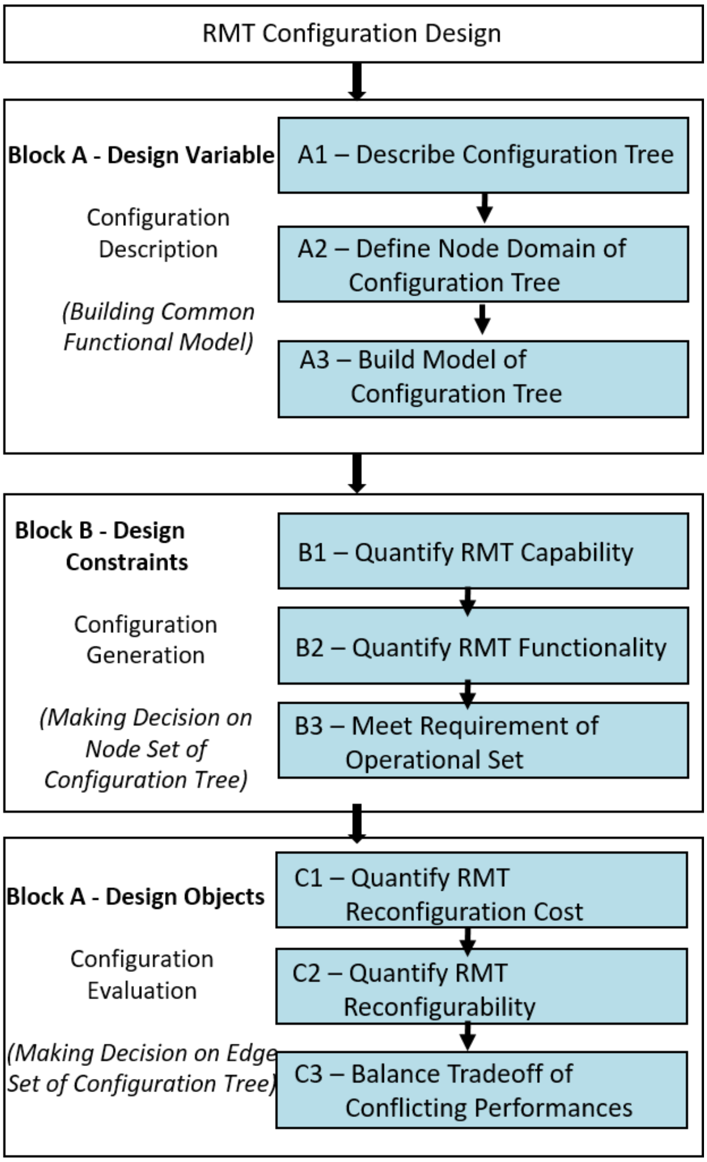



**Figure 6.5. Design Method for RMT Configuration**

- ***Configuration evaluation, Block C, Figure 6.5.*** The performance of the feasible configuration is evaluated with respect to cost and reconfigurability, which helps to make decisions on the edge set with the fixed node set. Therefore, in light of the trade-offs among multiple objectives, the most satisfactory RMT configuration tree is chosen. This enables the selected RMT configuration to satisfy the set of operational requirements with the trade-off between minimizing cost and maximizing reconfigurability.

In this dissertation, the assumption is that considered RMT is equipped with multiple-spindle head and due to the stiffness, and the maximizing number of spindle-head is set as three. As the smallest unit of design, we assume that there are only basic modules involving in the RMT configuration, which is the same as the reference (Mpofu, et al., 2008; Moon and Kota, 2002). The module library has limited module and different module is matched with the different functions. To simplify the design process, we adopt the extra assumptions based on the current manufacturing practice as the following:

1) Processing requirements are given and the task information includes the operation feature and the operation quantity;
2) Spindles heads in the same configuration are independent;
3) Modules are assembled via the standard interface, which is beneficial for the reconfiguration smoothness;
4) Errors in the cost of modules which has little influence on the exploration process; and
5) The sequence among the modules to be assembled, the module related to the x-axis motion has priority to be installed, the second is y-axis motion, and the third is z-axis motion and the final is the rotary, spindle head.

In summary, the RMT configuration design method includes the construction of a configuration tree, Figure 6.5, Block A, the construction of a constraint model, Figure 6.5, Block B, and the construction of an objective model, Figure 6.6, Block C, respectively, as elaborated in Sections 6.2.2, 6.2.3, and 6.2.4.

### 6.1.2 Construction of the Configuration Tree

A configuration tree is a functional model to describe an RMT configuration using a tree structure. Various nodes represent the modules of RMT configuration, and the edges represent the assembly relationship among modules. Based on a mapping relationship between RMT configuration and the configuration tree, the steps for construction of the configuration tree are identified, and the node library is defined to express the function of the modules. To quantize the design problem, a mathematical expression of the configuration tree is critical. Because of its data structure, the tree is expressed using sets.

***Analysis of a Configuration Tree (Figure 6.5, Block A, Steps A1 and A2).*** Given that the movements among the tools and the workpiece are independent of each other, each processing operation of the machine tool can be simplified to reflect the relative movement among several tools and the workpiece. Thus, the entire configuration design of the RMT is framed by tool-related configuration and workpiece-related configuration. The tool-related configuration of an RMT consists of modules related to tool movement. The workpiece-related configuration consists of modules which relate to workpiece movement. Because of these two sub-configurations of an RMT, the process of constructing a configuration tree has three steps.

1) Form the tool-side branch of the tree, which is mapped to the modules in the tool-related configuration;
2) Form the workpiece-side branch of the tree, which is mapped to the modules in the workpiece-related configuration; and
3) Form the complete tree with the workpiece-side branch and the tool-side branch. This maps the entire RMT configuration.

The cornerstone of constructing the configuration tree is the node library. To map the modules and the nodes, each node represents the carrier of a single module function. Hence, one node corresponds to a single module in the module library, while each module is also expressed as a node based on its function. Accordingly, when the number of modules in the RMT configuration increases, the corresponding tree has more nodes and edges. However, the computational complexity is increased as the size of tree increases. The nodes and edges in the tree structure have limited quantity. Considering manufacturing performance in the reality, the functions achieved in the machine tool is also limited. Consequently, in general, the tree can represent any normal size of RMT configuration.

**Table 6.1. Basic Node Domain of RMT Configuration Tree**

| Num. | Name | Node Function |
|---|---|---|
| 1 | Spindle Head | Modules with a variety of tools |
| 2 | Fixture | Modules for positioning the workpiece |
| 3 | Slide | Modules for moving tool and work-piece left and right |
| 4 | Cross-Slide | Modules for moving tool and work-piece forward and backward |
| 5 | Column | Modules for moving tool and work-piece up and down |
| 6 | Rotary table | Modules for allowing tool and work-piece rotary motion |
| 7 | Base | Modules for support and connection of the modules |

To express the procedure in detail, we list seven different nodes in Table 6.1 as an example to design the RMT configuration. The nodes are divided by function: the spindle head, fixture, slider, cross-slider, column and rotary table. To identify the appropriate location of a module in an assembly relationship, we define the parent-child relationship of edges in the configuration tree model. If one module can make another module move, the former is the parent node of the edge, and the latter becomes the child node.

***Model of a Configuration Tree (Figure 6.5, Block A, Step A3).*** In the process of RMT configuration design, a configuration tree is not directly involved as a design variable. Therefore, it is necessary to build a mathematical model of the configuration tree as follows:

$$CT = \{u, v | u \in U, v \in V\} \tag{6.1}$$

where

$CT$ : configuration tree,

$u$ : nodes,

$v$ : edges,

$U$ : node set of the RMT configuration tree, and

$V$ : edge set of the RMT configuration tree.

The definition of the node set *U* is:

$$U = \{u_{ijk} | i \in (1, \cdots, 7), j \in N, k \in 0,1\} \tag{6.2}$$

where

$u_{ijk}$ : element in the node set *U*,

$i$ : type of node, Table,

$j$ : identifier of the node of the same type, and

$k$ : section of the configuration tree to which the node belongs.

**Table 6.2. Variable *i* and** Corresponding **Node Type**

| i | $u_{ijk}$ | Node type |
|---|---|---|
| 1 | $u_{1jk}$ | Spindle Head |
| 2 | $u_{2jk}$ | Fixture |
| 3 | $u_{3jk}$ | Slide |
| 4 | $u_{4jk}$ | Cross-Slide |
| 5 | $u_{5jk}$ | Column |
| 6 | $u_{6jk}$ | Rotary table |
| 7 | $u_{7jk}$ | Base |

If *k*=0, the node belongs to the tool-side branch and if *k*=1 the node belongs to the workpiece-side branch.

An edge consists of two nodes in an ordered pair. Every node in the configuration tree can be described by Equation 6.2. Thus, the edge set *V* is expressed as follows:

$$V = \{v = \langle u_{ijk}, u_{i`j`k`} \rangle | f_1(v) = 1, u_{ijk}, u_{i`j`k`} \in U, i \neq i`\} \tag{6.3}$$

$$f_1(\langle u_{ijk}, u_{i^{`}j^{`}k^{`}}\rangle) = \begin{cases} 1\ existing\ the\ edge\ of\ u_{ijk}\ and\ u_{i^{`}j^{`}k^{`}} \\ 0\ non-existing\ the\ edge\ of\ u_{ijk}\ and\ u_{i^{`}j^{`}k^{`}} \end{cases} \quad (6.4)$$

where

| | |
|---|---|
| $v$ | : ordered pair which specifies one edge in the configuration, |
| $u_{ijk}$ | : parent node in the edge, and |
| $u_{i^{`}j^{`}k^{`}}$ | : child node. |

$f_1(<u_{ijk}, u_{i'j'k'}>)$ is a discriminant function of the edge. Further, when the function $f_1$ equals 1, the edge between $u_{ijk}$ and $u_{i'j'k'}$ exists in the configuration tree. On the other hand, when the function $f_1$ equal 0, there is no edge between $u_{ijk}$ and $u_{i'j'kp}$.

To ensure manufacturing stability, we assume the following rules for the assembly relationship among modules:

1) The modules for the same motion are always installed on different branches, and there is no assembly relationship among the modules on different branches. The mathematical expression of this rule is:

$$\langle u_{ijk}, u_{i^{`}j^{`}k^{`}}\rangle = 0$$
$$\sum_{k\neq k^{`}}\sum_{i^{`}}\sum_{j^{`}}\langle u_{ijk}, u_{i^{`}j^{`}k^{`}}\rangle = 0 \quad (6.5)$$

2) There is at most one assembly relationship between any two modules. The module cannot be assembled with itself. This rule is expressed by:

$$\sum_{j}\langle u_{ijk}, u_{i^{`}j^{`}k^{`}}\rangle = 0$$
$$\forall i^{`} \neq i \sum_{j^{`}}\langle u_{ijk}, u_{i^{`}j^{`}k^{`}}\rangle \leq 1 \quad (6.6)$$

3) The module with the tools and the module for the workpiece are always installed on different branches. This rule is given as follows:

$$\langle u_{1jk}, u_{2j^{`}k}\rangle\ and\ \langle u_{2jk}, u_{1j^{`}k}\rangle = 0 \quad (6.7)$$

4) A module for rotary motion is always installed on a module for linear motion. The rule is shown as follows:

$$\langle u_{6jk}, u_{3j`k}\rangle, \langle u_{6jk}, u_{4j`k}\rangle \; and \; \langle u_{6jk}, u_{5j`k}\rangle = 0 \tag{6.8}$$

5) For linear motion, a module for up and down motion is always installed on a module for forward and backward motion, while the module for forward and backward motion is always installed on a module for left and right motion. Hence, the rule is expressed by:

$$\langle u_{4jk}, u_{3j`k}\rangle, \langle u_{5jk}, u_{4j`k}\rangle \; and \; \langle u_{5jk}, u_{3j`k}\rangle = 0 \tag{6.9}$$

### 6.1.3 Construction of the Constraint Model

The construction of the constraint model is used to generate the set of feasible configuration trees, which are designed to satisfy the requirements from the operation set. The operation set corresponding to the RMT includes the quantity of the required operations and the features of those operations. To process of the operation set, the RMT is required to provide suitable capability and functionality. RMT capability refers to the number of operations which are finished by the RMT, measured by the number of tools in the RMT configuration. The RMT functionality refers to its operational features, measured by the relative motion between the RMT tool and the workpiece. Therefore, this process is used to establish mathematical expressions for capability and functionality, and then combine the processing parameters of the operational requirements, forming the constraint model.

***Capability of the Configuration Tree (Figure 6.5, Block B, Step B1).*** There is need for one-to-one relationship between the RMT tool and the required operations, i.e., the tool finishes one operation at a time. The greater the number of tools in the RMT configuration more operations are completed concurrently; therefore, the RMT capability is greater. In the node library, the spindle head is the module referring to the tool itself. Thus, capability is expressed as follows:

$$CCT = \sum_{j \in N} f_2(u_{1j0}) \tag{6.11}$$

where

| | |
|---|---|
| $CCT$ | : capability of the configuration tree *CT*, |
| $f_2(u)$ | : unction which determines whether $u_{1j0}$ belongs to configuration tree *CT*, |
| $u_{1j0}$ | : $j^{th}$ spindle head in the tool-side branch in the configuration tree, and |
| $\sum f(u)$ | : sum of the spindle heads in the configuration tree *C*T. |

If the configuration tree *CT* contains $u_{1j0}$, $f(u_{1j0})$ is equal to 1, otherwise is 0.

***Functionality of the Configuration Tree (****Error! Reference source not found.* ***igure 6.5, Block B, Step B2).*** The process of determining RMT operation is specifying the relative motion between the tool and the workpiece in the machine tool. Thus, the functionality requirement is described by relative motions. In kinematics, the degrees of freedom (DOF) is a measure used to express the motion. There are 6 axes in the DOFs to define the motion directions: X-, Y-, Z-, A-, B- and C- axes, as shown in Figure 6.6. The X-axis is used for left and right motions; the Y-axis is used for moving forward and backward; the Z-axis is used for moving up and down; the A-, B- and C-axes are used to express rotary motions on the X-, Y- and Z- axes respectively.

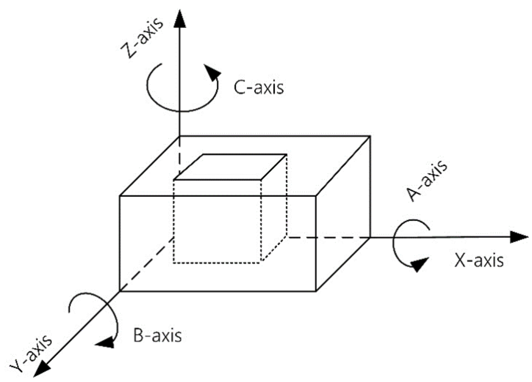


**Figure 6.6. The Six Axes of Degrees of Freedom**

In view of the DOF, arbitrary RMT functionality is described as a set of six motion directions. In the node library, the slide, cross-slide, column, and rotary table are all directional nodes that can be used to influence the motion of the tool and the workpiece. In Table 6.33, the mapping between the directional nodes and DOF is shown.

**Table 6.3. The Mapping Relationships among Directional Nodes and DOF**

| Primitive | Linear (L) axes | | | Rotary (R) axes | | |
|---|---|---|---|---|---|---|
| | X-axes | Y-axes | Z-axes | A-axes | B-axes | C-axes |
| Slide | 1 | 0 | 0 | 0 | 0 | 0 |
| Cross-slide | 0 | 1 | 0 | 0 | 0 | 0 |
| Column | 0 | 0 | 1 | 0 | 0 | 0 |
| Rotary table | 0 | 0 | 0 | 1 | 1 | 1 |

The functionality of an RMT is defined as follows:

$$T(u_{1j0}) = [t_{j1}t_{j2}t_{j3}t_{j4}t_{j5}t_{j6}] \quad (6.12)$$

$$H_{1x6} = [h_{11}h_{12}h_{13}h_{14}h_{15}h_{16}] \quad (6.13)$$

where

$T$ : motion of the tool-side branch in the configuration tree,

$t_{jr}$ : X-, Y-, Z-, A-, B- and C- axes (from left to right),

$H$ : motion of the workpiece-side branch in the configuration tree, and

$h_{1r}$ : X-, Y-, Z-, A-, B- and C- axes (from left to right).

In the matrix T, the element $t_{jr}$ is either 0 or 1. If the value of $t_{jr}$ is 0, the related tool cannot realize motion in this direction. If the value of $t_{jr}$ is 1, the motion can be realized. In matrix H, the element $h_{1r}$ is either 0 or 1. If the value of $h_{1r}$ is 0, the workpiece cannot realize motion in this direction. If the value of $h_{1r}$ is 1, motion in that direction can be achieved.

***Constrains from the Operational Set (Figure 6.5, Block B, Step B3).*** When the capability and functionality satisfy the requirements of the operational set, a feasible configuration tree is obtained. In terms of the operational set, a requirement is defined by the number of operations, $n$, and the features of the operations. The operational requirement is modeled as follows:

$$O_j = [o_{j1} o_{j2} o_{j3} o_{j4} o_{j5} o_{j6}] \quad (6.14)$$

where

$O_j$ : $j^{th}$ spindle head-related operation, and

$o_{jr}$ : degrees of freedom of motion on the X-, Y-, Z-, A-, B- and C- axes.

If the motion in this direction is needed for the operation, the related element $a_{jr}$ is equal to 1, otherwise it equals 0.

The constraint on capability is the number of spindle heads in the configuration tree is equal to the number of operations to be performed, while the constraint on functionality is that the motion realized by the direction nodes in the configuration tree agrees with the motion required by the operational features. Therefore, the constraint model, which is used to design the feasible configuration tree, is expressed as follows:

$$CCT = n \quad (6.15)$$

$$FCT = t_{lr} \oplus h_{1r} = o_{lr} \quad (6.16)$$

where

$CCT$ : capability of the configuration tree,

$n$ : number of operations,

$FCT$ : functionality of the configuration tree,

$t_{lr}$ : motion in the $r^{th}$ direction of the $l^{th}$ tool-related configuration,

$h_{1r}$ : dictates the motion in the $r^{th}$ direction of the workpiece-related configuration,

$o_{lr}$ : motion requirement for the $r^{th}$ direction of the $l^{th}$ operation, and

$\oplus$ : binary addition; that is, if $t_{lr}=0$ and $h_{1r}=0$, $t_{lr}\oplus h_{1r}=0$, else $t_{lr}\oplus h_{1r}=1$。

If the RMT needs to be reconfigured but the operations requirement (e.g., the features or quantity) are unknown, the parameters on the right side of the constraint model are undefined. Because future reconfiguration is unpredictable, RMT is required to be flexible enough to provide the required capability and functionality. Therefore, for incomplete operational requirement information, the constraint model must be modified. There are three different modes to address the incomplete information.

***Mode 1.*** The feature $O_j$ is unknown but the operation quantity $n$ is given. The corresponding modified constraint model is as follows:

$$CCT = n \tag{6.17}$$

$$\min FCT^{`} = \sum_{l=n} \sum_{r=6} \left(1 - (t_{lr}\oplus h_{1r})\right) \tag{6.18}$$

where

$FCT^{`}$ : flexibility of functionality in the RMT configuration.

The closer $t_{lr}\oplus h_{1r}$ is to 1, the smaller the value of $FCT'$.

***Mode 2.*** The feature $O_j$ is given but the operation quantity $n$ is unknown. The corresponding modified constraint model is as follows:

$$CCT \leq n_{max} \tag{6.19}$$

$$FCT = t_{lr}\oplus h_{1r} = o_{lr} \tag{6.20}$$

where

$n_{max}$ : maximum number of tools (spindle heads) in the RMT configuration.

***Mode 3.*** Both the feature $O_j$ and the operation quantity $n$ are unknown. The corresponding modified constraint model is as follows*:*

$$CCT \leq n_{max} \tag{6.21}$$

$$\min FCT^{`} = \sum_{l=n} \sum_{r=6} \left(1 - (t_{lr} \oplus h_{1r})\right) \tag{6.22}$$

Therefore, when the features and quantity of the required operations are known, Equations 6.15 and 6.16 are used as the constraint model. When at least one of the feature and quantity is unknown, the constraint model is modified into the corresponding mode.

#### 6.1.4 Construction of the Objective Model

Efficiency is the main prerequisite for ensuring the widespread use of configuration trees. After generating the set of feasible configuration trees, based on the performance we will select the most satisfactory configuration tree. Therefore, the selection process requires making decisions on the edge set of the configuration tree to solve trade-offs among multiple objectives. Compared with a conventional machine tool design process, RMTs is cost-effective with efficient reconfigurability. Cost-effective reconfiguration implies reduction in expenditure as much as possible in the reconfiguration process. Efficient reconfiguration requires that the modules in RMT configuration are as reusable as possible in the reconfiguration process.

***Cost of the Configuration Tree (Figure 6.5, Block C, Step C1).*** In the reconfiguration process, the alteration of edges leads to the addition, deletion, or moving of nodes. Based on node movement, the cost is divided into fixed and assembly costs. Fixed cost refers to the cost due to adding a node to the RMT configuration tree and assembly cost refers to the cost of altering a node in the RMT configuration tree. Assembly cost is directly proportional to number of node alterations. When the edge between two nodes is altered, the “number of node alterations” of the two nodes increases by 1. When a node is moved between different branches or deleted from the configuration, the labor loss and the installation time increases, so the “number of node alterations” of the two nodes increases by 2. Hence, the quantitative model of the cost for an RMT configuration design is:

$$ECT = \sum_{u \in U_i^{`}} g(u) + \sum_{u \in U_i^{`}} q(u) \times s(u) \tag{6.23}$$

where

$ECT$ : cost of a configuration tree,

$\sum_{u \in U_i^{`}} g(u)$ : fixed cost, and

$\sum_{u \in U_i^{`}} q(u) \times s(u)$ : assembly cost.

***Reconfigurability of the Configuration Tree (Figure 6.5, Block C, Step C2).*** Reconfigurability refers to the degree of difficulty of reconfiguring the configuration. If more edges are altered from the previous to the next configuration tree it is more difficult to complete the reconfiguration. Reconfigurability is affected by the similarity and sustainability of configurations due to reconfiguration relationship between two consecutive RMT configurations. In this context, configuration similarity refers to the utilization of the edges of the previous configuration tree in the current configuration tree. A higher utilization has a positive impact on the reconfigurability of the configuration tree. Configuration sustainability refers to the probability that the edges of the current configuration tree are same to those of the next configuration tree. A higher probability has a greater positive impact on reconfigurability of the configuration tree. Therefore, the quantitative models for the reconfigurability of the RMT configuration tree are:

$$RCT = UCT + PCT \tag{6.24}$$

$$UCT = \frac{card(V^`)}{card(V)} \tag{6.25}$$

$$PCT = \sum_{v \in V} p(v) \tag{6.26}$$

where

| | |
|---|---|
| $RCT$ | : reconfigurability of the RMT configuration tree, |
| $UCT$ | : edge utilization rate of an RMT configuration tree, |
| $V$ | : set of edges in an RMT configuration tree, |
| $V^`$ | : set of edges that are the same in the current and previous configuration trees, |
| $card$ | : number of elements in the set, |
| $card(V)$ | : number of edges in an RMT configuration tree, |
| $PCT$ | : probability of the configuration tree, and |
| $p(v)$ | : probability that edge *v* of the current configuration tree exists in the edge set of the next configuration tree. |

Higher values of $RCT$ indicate a greater reconfigurability for the RMT configuration tree. Each branch of an RMT configuration tree allows up to four DOFs. Different DOF sets correspond to different node sets, which corresponds to different edge sets. Based on the combinations of six DOFs, a configuration tree has 15 candidate edge set schemes, as shown in Table 6.4. The probability that edge *v* appears, *h(v),* is equal to the frequency at which this edge appears in the 15 candidate edge sets.

**Table 6.4. The Value of *p(v)***

| # | Edge Subset *v* | *p(v)* |
|---|---|---|
| 1 | <$u_{7jk}$, $u_{3jk}$> | 8/15 |
| 2 | <$u_{7jk}$, $u_{4jk}$> | 4/15 |
| 3 | <$u_{7jk}$, $u_{5jk}$> | 2/15 |

| | | |
|---|---|---|
| 4 | $<u_{7jk}, u_{5jk}>$ | 1/15 |
| 5 | $<u_{7jk}, u_{3jk}>, <u_{3jk}, u_{4jk}>$ | 4/15 |
| 6 | $<u_{7jk}, u_{3jk}>, <u_{3jk}, u_{5jk}>$ | 2/15 |
| 7 | $<u_{7jk}, u_{3jk}>, <u_{3jk}, u_{5jk}>$ | 1/15 |
| 8 | $<u_{7jk}, u_{4jk}>, <u_{4jk}, u_{5jk}>$ | 4/15 |
| 9 | $<u_{7jk}, u_{4jk}>, <u_{4jk}, u_{5jk}>$ | 2/15 |
| 10 | $<u_{7jk}, u_{5jk}>, <u_{5jk}, u_{5jk}>$ | 4/15 |
| 11 | $<u_{7jk}, u_{3jk}>, <u_{3jk}, u_{4jk}>, <u_{4jk}, u_{5jk}>$ | 2/15 |
| 12 | $<u_{7jk}, u_{3jk}>, <u_{3jk}, u_{4jk}>, <u_{4jk}, u_{5jk}>$ | 1/15 |
| 13 | $<u_{7jk}, u_{3jk}>, <u_{3jk}, u_{5jk}>, <u_{5jk}, u_{5jk}>$ | 1/15 |
| 14 | $<u_{7jk}, u_{4jk}>, <u_{4jk}, u_{5jk}>, <u_{5jk}, u_{5jk}>$ | 2/15 |
| 15 | $<u_{7jk}, u_{3jk}>, <u_{3jk}, u_{4jk}>, <u_{4jk}, u_{5jk}>, <u_{5jk}, u_{5jk}>$ | 1/15 |

***Decision-Making for Multiple Performance Measures (Figure 6.5, Block C, Step C3).*** The decision-making process for the edges of an RMT configuration tree uses weighted objectives: minimize cost while maximizing reconfigurability. To give a uniform format for the objective functions, the expressions for the capability and reconfigurability are normalized. Meanwhile, a deviation variable is introduced to describe how much the proposed scheme deviates from the most satisfactory value of the objective. The method of developing expressions for cost, ECT, and reconfigurability, RCT, are given by:

$$\frac{min(ECT)}{ECT} + d_{m1} = 1 \quad (6.27)$$

$$\frac{RCT}{max(RCT)} + d_{m2} = 1 \quad (6.28)$$

where

$m$ : number of feasible configuration trees,

$d_{m1}$ : deviation of the cost of the $m^{th}$ feasible configuration tree, and

$d_{m2}$ : deviation of the reconfigurability from the most satisfactory reconfigurability.

The most satisfactory configuration tree has the smallest sum of deviations. Furthermore, based on the actual production processing, designers focus on different aspects of performance. When an RMT is used for processing various small batches of parts, the particular emphasis of design is placed on reconfigurability. When an RMT is used for processing simple, large batches of parts, the particular emphasis is cost. Therefore, a weighting coefficient is introduced to signify priorities. To select the satisfactory configuration tree, the decision-making model is as follows:

$$minI = w_1 d_{m1} + w_2 d_{m2} \tag{6.29}$$

where

| | |
|---|---|
| $I$ | : decision-making function, |
| $w_1$ | : weights of cost, and |
| $w_2$ | : weights reconfigurability. |

The value of index *I* represents the standard for making the decision, when this value is close to 0, the corresponding scheme has a smaller deviation from the target value. Weights are determined by experts based on experience, where the sum of $w_1$ and $w_2$ equals one. When it is preferred to maintain product diversity, the value of $w_2$ is greater than $w_1$. When it is preferred to reduce cost, the value of $w_1$ is greater than $w_2$.

## 6.2 Reconfigurable Inspection System (RIS) Design in Dynamic Management

In this section Reconfigurable Inspection System design is presented. Development of RIS configuration design is presented in Section 6.3.1. Further, development of specific model-based procedure for RIS configuration design is presented in Section 6.3.2.

### 6.2.1 Development of RIS Configuration Design

The manufacturing process in the RMS, Figure 6.7, has multiple stages. The workpieces are machined into products through multiple operations. To ensure excellent quality, there are 4 types of component, namely, operational stations, inspection stations, a delivery system and a return system. The operational stations (i.e., Stations 1, 2, 4,…, n+k-1) machine one or more operations via RMTs, while the inspection stations (i.e., Stations 3,…, n+k) measure the product quality during the process via RISs. The workpiece is transferred from one station to the next using the delivery system. When errors are detected by inspection stations, the return system is used to return the workpiece to related upstream operational stations. Therefore, the RIS in the $k^{th}$ inspection station focuses on detecting its upstream operational stations, which are behind the $k-1^{th}$ inspection station.

In a traditional manufacturing system, the inspection station is usually at the end of the line. End-of-line detection is popular approach in the industry and cost-effective. However, only some of the errors can be detected, and due to delayed detection the quality of product is reduced. On the other hand, in saturated detection each operational station is followed by an inspection station, which result with high quality of product. However, this approach is very costly. Therefore, we need to select a minimal but sufficient number of inspection stations to detect the manufacturing process. That is, the configuration design of the RIS should balance the trade-off between cost and diagnosability in the RMS's manufacturing process.

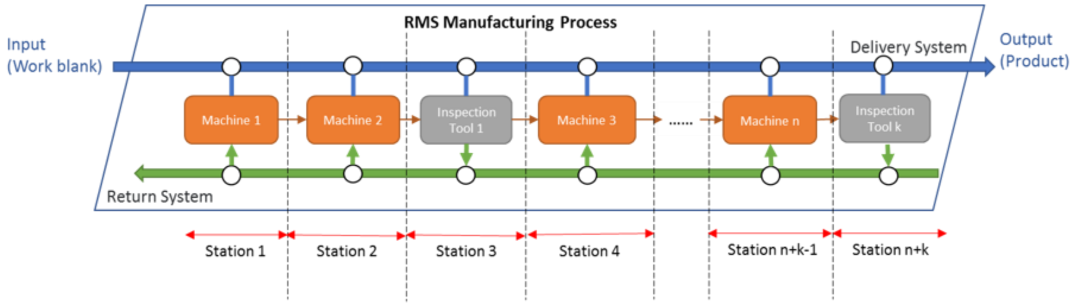



**Figure 6.7. Manufacturing Process in the RMS**

*Detection Mechanism via RIS*

In the RMS, the manufacturing process includes multiple operations, and the quality of the product is affected by the processing parameters of the operational stations. During the RMS's lifecycle, deviations in the processing parameters leads to variations in the product quality. Variations can propagate and accumulate among the stations. The influences of the different stations on the product quality are interrelated, and this interrelatedness creates a complex flow of information through the manufacturing process. To describe the information flow, SoV theory is used (Shang, et al., 2018). This theory clearly models the accumulation and propagation of errors in the production process as shown in Figure 6.8.

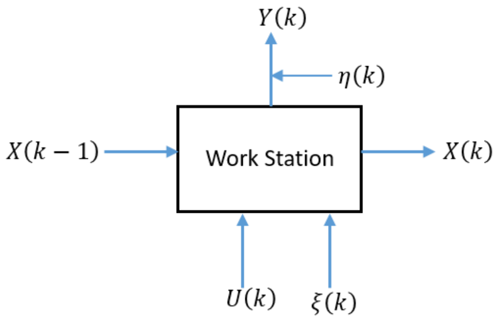



**Figure 6.8. Information Flow at One Station Based on SoV Theory**

Identifying the root causes of errors using SoV theory, Chapter 3, Section, relies on the RIS configuration design as a basis for error diagnosis. Combined with SoV theory, the RMS detection process is shown in Figure 3.7.

The essence of identifying root causes via SoV theory is to simulate the manufacturing process, Equation 3.1. A product quality error refers to a deviation of the actual position from the ideal position, and the main types of error include fixturing error caused by imperfect locators, datum errors caused by errors in the datum feature, and machine tool errors caused by loops in the machine's structure. Fixture and machine tool errors are part of the current station, whereas datum errors are influenced by other stations. Therefore, a virtual station is simulated using data from datum measurements. If the virtual station is in the same state as the corresponding real station, the real station is of high quality; otherwise, the station should be maintained or updated. When the SoV is used to identify the root cause of errors, it is paramount that the quality features of the product and the datum of the processing feature are detected.

*Key Features of the RIS for Reconfiguration*

In the dynamic manufacturing process, the main function of an RIS is to ensure the quality of the final product. The RIS can quickly adjust its detection functionality and detection capability. Detection functionality refers to the product features that the RIS can detect, and detection capability refers to the RIS's sensitivity to product errors. The RIS divides the manufacturing process into several production line partitions. The RIM is more sensitive when there are fewer machine tools in the production line partition. Because the RIS is a component of the RMS, the reconfiguration design principle of the RMS is available to the RIS design. Combined with the functions of the RIS (i.e., detection), the six key features are discussed in the following.

***Modularity.*** We combine different RIMs to form diverse RIS configurations and reconfigure the RIS by changing the RIM layout. For example, the RIS can provide different detection functionality and capability by changing the number of RIMs and their positions, and a RIM can perform different detection tasks by changing its sensors. However, an excessive number of RIMs in an RIS can result in high management costs and increase the system's ramp-up time. Similarly, having too many sensors in an RIM increases the structural complexity and decreases the equipment's reliability. Therefore, the modularity of the RIS requires determination of a reasonable assignment of detection tasks and then, selection of the minimum sufficient number of RIMs and sensors. We assume that one processing feature can be detected by each sensor. Based on the above description of the detection mechanism, the number of products is related to each process feature and its datum feature. The number of sensors in an RIM is proportional to the processing characteristics measured by the RIM.

***Integrability.*** Standardization of interfaces in an RIM, which is beneficial for the introduction of the modern technologies or new devices. When the number of sensors in an RIM is small and the number of idle interfaces is large RIS has a greater configuration flexibility. The high flexibility of the RIS reduces the reconstruction time and cost. Hence, integrability requires the RIS to determine a reasonable sensor density and select the corresponding number of sensors. In addition, the ease of RIM reconfiguration is governed by the degree of sensor change. Therefore, the reconfiguration time and cost are proportional to the number of sensor changes.

***Convertibility.*** Ability of the RIS to quickly adjust its detection functionality based on the process route. The RIS can change its detection functionality to satisfy the requirements of different parts or part families. The RIS provides the required detection functionality by adding, deleting, or replacing sensors. Ensuring product quality allows the RIS to detect all the product features. Accordingly, different product features alter the RIS's detection functionality. Therefore, convertibility enables the RIS to detect the manufacturing process by selecting a sufficient number of RIMs and sensors. That is, the number of sensors should be greater than the number of detected product features, which ensures that quality errors in each production line can be detected. At the same time, when the product features change, we consider changing the number of sensors to change the RIS's detection functionality.

***Scalability.*** Ability of the RIS to rapidly adjust its detection capability according to the process route. That is, we adjust an RIM's position according to the processing route to detect each operation in timely manner. Timely detection of an operation refers to direct monitoring of the process as much as possible, i.e., decreasing the distance between an RIM the operational station increases the error sensitivity of the RIM. Conversely, if the distance between the RIM and the operational station is greater, the RIM cannot detect the quality error in time, resulting in unnecessary waste. Therefore, scalability requires the RIS to locate the RIM close to the operation. As the operation changes, the position of the RIM changes, minimizing the distance between the RIM and the operations.

***Customization.*** Design RIS configuration based on the quality detection required by a given process route while minimizing the redundant detection functionality and detection capabilities. The customizability of RIS is measured by its device utilization. RIS is more customizable for higher device utilization rates. Therefore, the customizability of the RIS requires that it maximize its utilization of equipment to select the appropriate number of RIMs for the required number of sensors. As the process route changes, the RIS adds the required equipment while removing unnecessary equipment to avoid redundancy.

***Diagnosability.*** Validity and timeliness of the data collected by the RIS, which determines whether the data collected meet the needs of the root cause diagnosis process. The validity of data refers to the degree of influence of the device reliability on data acquisition. The timeliness of data refers to the duration of the fault from generation to detection. Therefore, the diagnosability of the RIS requires to select enough RIMs and sensors based on device reliability and the detection range while installing each RIM in a reasonable location. If the complexity of the RIS's device structure is lower, the device reliability is higher. As a result, the impact of the device on data acquisition is smaller, which makes the data more efficient. If the RIS's equipment distribution density is larger, the detection range is smaller. As a result, the data are available sooner if the device collects them faster.

Analysis of the key features shows that diagnosability is the core of the six key RIS features, and the remaining five are designed to support diagnosability. In summary, the essence of the RIS's configuration design is to provide quality detection in the reconfiguration process through the number of RIMs and their locations as well as the number of sensors, where a satisfactory configuration has the key features, especially diagnosability.

***Overview of RIS Configuration Design.*** Maintaining an excellent manufacturing process in RMS necessitates reconfiguration at each available point. In the RMS, the use of an RIS and RIMs to collect data not only provides a basis for quality assurance and process testing but also enhances the quality of the system-related process fault diagnosis. According to the analysis of the key features in the previous section, the ability of the RIS to collect data depends on its configuration design. At present, researchers mainly focus on discussing the concept of detection or control system architecture. There is a lack of research on the physical configuration design of the detection system. Therefore, we present a key-feature-based method for RIS configuration design. The specific process is as follows:

***Building an RIS Configuration Design Model.*** The basis of the proposed method, which is Section 6.2.2. Due to the basic components of an RIS, the design variables are defined as the number of RIMs, their positions, and the number of sensors. The design variables are mathematically described using vectors. Then, the process route is analyzed, a mathematical model of it is constructed, and the configuration's design parameters are extracted.

***Exploring Feasible RIS Configuration Schemes.*** The core of the proposed method, Section 6.3.2. The fundamental goal of an RIS is to detect the processing route. Therefore, in the process of RIS configuration design, the constraints of the configuration design are modeled according to the RIS's detection capability and detection functionality for the process route. Feasible RIS configuration schemes are generated.

***Decision-making based on a Satisfactory RMT Configuration Scheme.*** The key to the proposed method, Section 6.4. The final goal of the RIS is to increase the efficiency of the detection process. Therefore, we use cost and diagnosability to evaluate each RIS configuration, and the most satisfactory configuration design is selected with the goal of minimizing cost and maximizing diagnosability.

### 6.2.2 Specific Model-Based Procedure for RIS Configuration Design

RIS is composed of multiple RIMs. Different numbers or positions of RIMs generate different RIS configurations, where each RIM is composed of multiple sensors. Different sensors represent different detection functionalities and capabilities, which affects the RIS's detection process. Hence, the RIS configuration design variables include the number of RIMs, the positions of the RIMs and the number of sensors. Based on these sets, we build a mathematical model to describe a RIM configuration as shown in the Equations 6.30 and 6.31:

$$CRIS = \{cr_1, cr_2, L, cr_M\} \tag{6.30}$$

$$cr_i = (y_i, x_i) \tag{6.31}$$

where

| | |
|---|---|
| $CRIS$ | : RIS configuration, |
| $cr_i$ | : the $i^{th}$ RIM in the RMS, |
| $M$ | : the number of RIMs, |
| $y_i$ | : position of the $i^{th}$ RIM, where RIM follows the $y_i^{th}$ RIT, and |
| $x_i$ | : number of sensors in the $i^{th}$ RMT, where RIM can detect $x_i$ features. |

A processing route is a requirement for any RIS configuration design. In view of the importance of product features to product quality, the process route should be considered while designing the RIS configuration. A better description of the RIS design process, based on a set of mathematical descriptions of the process:

$$C_p = \{cp_1, cp_2, L, cp_N\} \tag{6.32}$$

where

$C_p$ : processing route,

$cp_i$ : the i$^{th}$ operation, and

$N$ : the number of operations in processing route $C_p$.

Based on the model of the RMS configuration and the processing route, constraints and goals are modeled as follows.

***Modeling the RIS Constraint Design.*** The RIS configuration constraint model is developed to explore the feasible domain of the RIS configuration design, in order to detect product quality based on the processing route. Quality detection is related to the ability to inspect errors and identify their root causes, which is a hard constraint for RIS configuration design. RIS can successfully provide a quality detection process if and only if its detection capabilities and the detection capabilities provided by the RIS configuration satisfy the processing route's quality requirements. The process of designing a feasible RIS configuration is as follows: establish a mathematical model with the detection functionality and capabilities necessary to create a feasible model of the domain design constraints and then, extract the routing parameters of the design process within the constraint model to obtain all feasible RIS configuration designs.

***Construction of the Detection Functionality Model.*** Detection tools in an RIS are sensors. Each sensor detects an operational feature. Therefore, more operational features are detected when there are more sensors, which improves the detection functionality. Detection functionality is expressed by the number of sensors:

$$FCRIS = \sum_{i=1}^{M} x_i \tag{6.33}$$

where

| | |
|---|---|
| $FCRIS$ | : detection functionality of the RIS configuration, |
| $x_i$ | : the number of sensors in the $i^{th}$ RIM, and |
| $M$ | : the number of RISs. |

***Construction of the Detection Capability Model.*** Detection capability of the RIS is described by its sensitivity to quality errors. The sensitivity to errors is essentially the time at which the RIS detects a quality error after it occurs. We assume that the delivery time for the product in the system is constant. The length of time before a fault is detected is expressed as the distance from the fault station to its near-detection machine. Therefore, we construct the mathematical expression for the detection capability of an RIS:

$$CCRIS = \frac{\sum_{i=1}^{m} \sum_{j=y_{i-1}+1}^{j=y_i} (y_i - j)}{\frac{(N-1) \times N}{2}} \tag{6.34}$$

where

| | |
|---|---|
| $CCRIS$ | : detection capability of the RIS configuration, |
| $y_i$ | : position of the $i^{th}$ RIM in the RIS, |
| $y_0$ | : distance from the $j^{th}$ operation to the $i^{th}$ RIM, |
| $\sum_{j=y_{i-1}+1}^{j=y_i} (y_i - j)$ | : sensitivity to error of the $i^{th}$ RIM, and |
| $N$ | : the number of RMTs in the RMS. |

*CCRIS* has a value in [0, 1]. When *CCRIS* is closer to 0, the detection capability of the RIS is higher.

***Modeling Constraints with Detection Functionality and Capability***. Feasible RIS configuration design is when the detection functionality and capability satisfy the product quality requirements. Detecting the processing route requirements are the number of processes N, the characteristic surface of the product $FCP = (f_1, f_2, \cdots, f_{CM})$, the number of characteristic surfaces of the product CM, and the fault diagnosis distance T. The fault diagnosis distance T is the least upper bound on the distance between the fault station and its corresponding inspection station. Based on the processing route, the constraint model of the RIS configuration design is discussed based on the two aspects of detection functionality and detection capability. On the one hand, the number of processes and the surface of the product features in the processing route are constrained by the RIS's detection functionality, which indicates that the number of sensors in the RIS configuration is not less than the number of product features involved in the process. On the other hand, the number of processes in the processing route and the fault diagnosis distance constrain the RIS's detection capability. That is, the position of the RIM determines the distance available for detecting the error. Therefore, the constraint model used to design feasible RIS configurations:

$$\begin{cases} FCRIS \geq \sum_{i=1}^{N} \sum_{j=1}^{CM} H(cp_i, f_j) \times \left( \sum_{k=1, k \neq j}^{CM} G(f_k) + 1 \right) \\ CCRIS \leq \dfrac{D(T) \times INT\left(\frac{N}{T}\right) + D(N - T \times INT\left(\frac{N}{T}\right))}{D(N)} \\ 1 \leq M \leq N \end{cases} \tag{6.35}$$

where

$FCRIS$ : constraints on the detection functionality of the RIS configuration design,

$H(*)$ : judgement function of the processing surface,

$G(*)$ : judgement function of the datum surface,

$CCRIS$ : constraint on the detection capability,

$D(*)$ : operation, and

$INT(*)$ : function used to retain the whole number.

If surface $f_j$ is machined in operation $cp_i$, then, $H(cp_i, f_j)$ is equal to 1; otherwise, it is equal to 0. If surface $f_k$ is the datum of surface $f_j$, then, $G(f_k)$ is equal to 1; otherwise, it is equal to 0.

***Modeling the RIS Design Goal.*** The low cost and high diagnosability of the RIS configuration is the motivation for improving an RMS's efficiency and reducing ramp-up time. The low cost of an RIS design refers to minimized design costs and resource waste, such as management costs, scrap costs and so on. The high diagnosability of an RIS design refers to maximized data collection performance, including timeliness, comprehensiveness, and effectiveness. Therefore, we consider two goals, cost and diagnosability, in evaluating configurations. In addition, each decision about an RIS configuration design is weighed against the multi-goal conflict process. The process is analyzing and establishing the cost and diagnosability models for the RIS configuration design. Further, establishing a design decision model based on the two mentioned quantitative models. A satisfactory RIS configuration is identified by solving the model.

***Construction of the Cost Model.*** Different RIS configurations have different numbers of RIMs and sensors, resulting in different design costs. The design cost is the cost of adding RIMs and sensors to the RIS configuration, related to the number of new additions to the configuration design. As the RIS's product inspection becomes increasingly accurate, more RIMs and sensors are needed in the RIS design, and the cost of the RIS design increases. Increasing the RIS as much as possible increases the design flexibility with regard to sensors and decreases the flexibility of the RIM design. Based on the above analysis, a quantitative model of the economic costs of RIM configuration:

$$ECRIS = \sum_{i=1}^{M} (c_1 + x_i \times c_2) \tag{6.36}$$

where

| | |
|---|---|
| $ECRIS$ | : cost of RIS configuration, |
| $c_1$ | : fixed average cost of installing an RIM, |
| $c_2$ | : fixed average cost of installing a sensor, |
| $x_i$ | : number of sensors in $i^{th}$ RIM, and |
| $M$ | : number of RIMs in the RIS. |

***Construction of the Diagnosability Model.*** Diagnosability is crucial to RIS configuration design, and its goal is to ensure the validity and timeliness of collecting process data. In the RIS, both the RIMs and the sensors have certain levels of reliability. Only when a sensor is in its normal state data can be collected and used in fault diagnosis; otherwise, the data are invalid. On the other hand, when an error cannot be found on time, the system produces product of bad quality. Later an error is detected more serious damage to the product is, greater the number of late errors is the system is damaged more. The degree of damage to the system is defined as the number of workstations traversed from the failed process to the test equipment. The timeliness of the data is defined as the average of the reciprocal of the maximum degree of damage to the system for each line segment. When this value is close to 1, the data are timelier, which represents less damage to the system. Based on the above analysis, an RIS constructs the quantitative models of the diagnosability:

$$RCRIS = XCRIS \times TCRIS \tag{6.37}$$

$$XCRIS = \frac{\sum_{i=1}^{M} p(x_1 + x_2 + \cdots + x_M)}{M} \tag{6.38}$$

$$TCRIS = \frac{\sum_{i=1}^{M} \frac{1}{(y_i - y_{i-1})}}{M} \tag{6.39}$$

where

$RCRIS$ : diagnosability of the RIS configuration,

$XCRIS$ : validity of the RIS configuration design,

$p_k$ : validity of the $k^{th}$ *sensor*,

$y_i$ : position of the $i^{th}$ RIM in the RIS, and

$y_i - y_{i-1}$ : expresses the maximum amount of damage done to the product in the process.

***Modeling Goals with the Cost and Diagnosability.*** The decision-making process for the RIS configuration design uses weighted goals to minimize cost and maximize diagnosability. RIS diagnosability will make some compromises when costs are as low as possible, and RMT costs may increase in terms of diagnostics. Therefore, cost and diagnosability are conflicting goals. The decision-making process of the optimal design involves a trade-off between these two goals. To give the goal functions a uniform format, the data for the cost and diagnosability are normalized and a deviation variable is introduced to describe how much the proposed scheme deviates from the most satisfactory value of the goal. The cost and diagnosability are re-expressed as:

$$\frac{min(ECRIS)}{ECRIS} + d_{g1} = 1 \tag{6.40}$$

$$\frac{RCRIS}{max(RCRIS)} + d_{g2} = 1 \tag{6.41}$$

where

$d_{g1}$ : deviation of the cost of the $g^{th}$ feasible RIS configuration, and

$d_{g2}$ : represents the diagnosability deviation.

A feasible configuration design of RIS tradeoff between cost and diagnosability. That is, it minimizes the sum of the cost and diagnosability deviations. However, in actual production situations, designers focus on different levels of economic cost and diagnosability. Therefore, we introduce a weight coefficient to represent the priority of the target. RIS configuration that uses the weight coefficient to select the goal:

$$minI = a_1 d_{g1} + a_2 d_{g2} \tag{6.42}$$

where

$I$ : decision-making function, which is the sum of $d_{g1}$ and $d_{g2}$, and

$a_i$ : weights of the cost and the diagnosability, experience based.

The sum of $a_1$ and $a_2$ is one. When maintaining product quality is preferred, $a_2$ is greater than $a_1$. When cost reduction is preferred, the $a_1$ is greater than $a_2$.

## 6.3 Integration Reconfiguration Design and Exploration of Systemic Reconfiguration Strategy

In this section we will explain Reconfigurable Manufacturing System (RMS) multi-granularity configuration, Section 6.4.1. Further, exploration of the RMS reconfiguration strategy through the proposed method, Section 6.4.2. The Reconfigurable Machine Tool (RMT) and Reconfigurable Inspection System (RIS) cDSP Models for decision-making in RMS configuration design are presented in

Section 6.4.3. The Reconfigurable Machine Tool (RMT) and Reconfigurable Inspection System (RIS) game theory-based model for interactions in RMS Configuration design are presented in Section 6.4.4. In the end, a decision network for exploring the RMS reconfiguration strategy is presented in Section 6.4.5.

### 6.3.1 RMS Multi-Granularity Configuration

Reconfigurable Manufacturing System (RMS) is a typical multi-stage manufacturing process, consisting of a series of chain workstations. Nowadays, it is required to design RMS to have cost-effective scale production adaptable to dynamically changing manufacturing environment. Thus, RMS is designed to adjust capabilities and functions for several part families, while maximizing the use of existing resources to reconfigure or update the manufacturing process. The main elements of RMS are Reconfigurable Machine Tool (RMT) and Reconfigurable Inspection Machine (RIM). RMT plays the role of manufacturing the blank or the intermediate product, while RIM performs the quality inspection on the intermediate product or final product. RMT and RIM consists of the modular components, such as mechanical and sensing modules. On the other hand, all of RMTs in RMS are considered as the subsystem to perform the customized production, called Reconfigurable Production Subsystem. The RIMs are formed into another subsystem, called Reconfigurable Inspection System (RIS), for providing full real-time detection. Facing the RMS multi-granular configuration, the reconfiguration takes place on two different scales time and space. According to the different time scales and concerns, the RMS configuration design is divided into module granularity, equipment granularity, and system granularity.

***Module Granularity Design (MGD).*** MGD refers to the configuration design on the minimum space-time dimension, such as the configuration design of a RMT or

RIM. MGD is the foundation of system strategy exploration, as the finest granularity. The input to the MGD is the module library and operation requirements. The output is the configuration design of the device. The essence of the design process mainly revolves around operation requirements, adding, deleting, or moving modules to make the equipment configuration change.

***Device Granularity Design (DGD).*** DGD takes the equipment as the design unit, and its space-time scale is larger than the MGD. The input to the DGD is the equipment library and process requirements, and the output is the subsystem configuration design. The essence of the DGD mainly revolves around the process requirements, adding, deleting, or moving the equipment, resulting in changes in the configuration of the subsystem.

***System Granularity Design (SGD).*** SGD is the concurrent design of multiple subsystems, and it needs to be represented on a larger spatial scale. The SGD input is the subsystem configuration design, such as the production system, the control system, and the market demands. The output is the overall system configuration design. The SGD is based on the overall characteristics of the system as a whole, and the system is adjusted and integrated to achieve better resource allocation.

The dynamic requirement leads to the reconfiguration on different scale and accordingly needs to consider the configuration design of different granularities. The smaller the granularity of the configuration is, the exploration emphasizes on the ability to grasp details. According to the bottom-up design principle of mechanical design, the manufacturing system is usually assembled from MGD to SGD, followed by device assembly, subsystem assembly, and then integrating all the subsystem assembly into a whole. In the manufacturing process, the design goal of each device is to complete its corresponding operation task. The design goal of the subsystem is the production or testing of processing one part families. And the entire system completes the production and inspection of the manufacturing process for the diverse part families. In addition, the production or detection of subsystems depends on the functions and capabilities of their corresponding devices. The production or detection of a system depends on the functions and capabilities of its subsystems. It can be seen that there is an interactive relationship between different granular configurations, especially the match between production and detection. The ultimate goal of the multi-granularity configuration analysis of this topic is to integrate the different granularity configuration designs on the basis of interaction relationship to realize the overall design.

The RMS's single granular configuration design includes three steps: design goal determination, performance analysis, and solution space exploration. The design goal of the microscopic granularity depends on the macroscopic granular configuration design scheme, while the microscopic granular configuration design can adjust the design variables of the macroscopic granular configuration design and support the macroscopic granular configuration analysis. When the system receives a new order, the designer formulates the product design parameters according to the customer's requirements, and analyzes the functions and capabilities required for the manufacturing system. Thereby, the preliminary RMS configuration for SGD is explored. Then, according to the RMS configuration scheme, the specific production process and the requirements of the inspection process are analyzed, where the design of the production subsystem and the detection subsystem is explored respectively. The production subsystem configuration determines the layout of the RMTs and their specific operation tasks. Based on the operation tasks, the configuration of each RMT can be identified. Similarly, the configuration of the detection subsystem determines the RIM layout and its detection tasks. The RIM configuration is determined according to the detection tasks. However, when a certain granular configuration is reconfigured, its functions and capabilities will change, which will affect the performance of the macroscopic granularity, and thus a new optimized design of the macroscopic particle size configuration is needed. Therefore, the reconstruction process of the RMS not only requires the support of a single-granularity configuration design, but also considers the interaction of different granularities. In this dissertation, the reconfiguration strategy of RMS multi-granularity configuration is defined as the integration of the RMT, related to the production performance, and the RIS configuration design, related to the detection performance.

### 6.3.2 Workflow of the Proposed Method

RMS reconstruction process is a complex problem due to the multi-granularity characteristics. The design process requires a large amount of manufacturing knowledge to support and adjust mechanical design. It is designed to meet the production and inspection requirements at different granularities. However, repeated iterations and changes may result in reduced work efficiency. The key to RMS reconfiguration to consider the configuration, design process of cooperation, and cooperation between different granularities. Implementing a concurrent design of multi-granular configurations requires solving the following three main problems:

***1) Information collection.*** During the design process, different design activities need to exchange and integrate information, and complete the decision based on the comprehensive design information. This condition requires that the design activities are mutually understood and no additional instructions need to be added. However, RMS refactoring involves different granularity or design of production and inspection, leading to diversified knowledge information. Therefore, the system design needs a standardized model to promote parallel design among multiple activities.

***2) Activity interaction.*** In design process there are interactions between different design activities, and the decision results of each activity may affect the decisions of other activities, resulting in different design overall performance. System design requires simulation of interactive interactions to reduce unnecessary optimization iterations, due to the interaction between different granular configurations of RMS refactoring.

***3) Explore the overall design plan.*** The exploration of the final overall design plan needs to integrate the information collection and activity interaction model and complete them under their interaction. Therefore, the system design needs to construct a decision network description RMS configuration design and realize the integration of the activity model of Steps 1 and 2 in the reconstruction process.

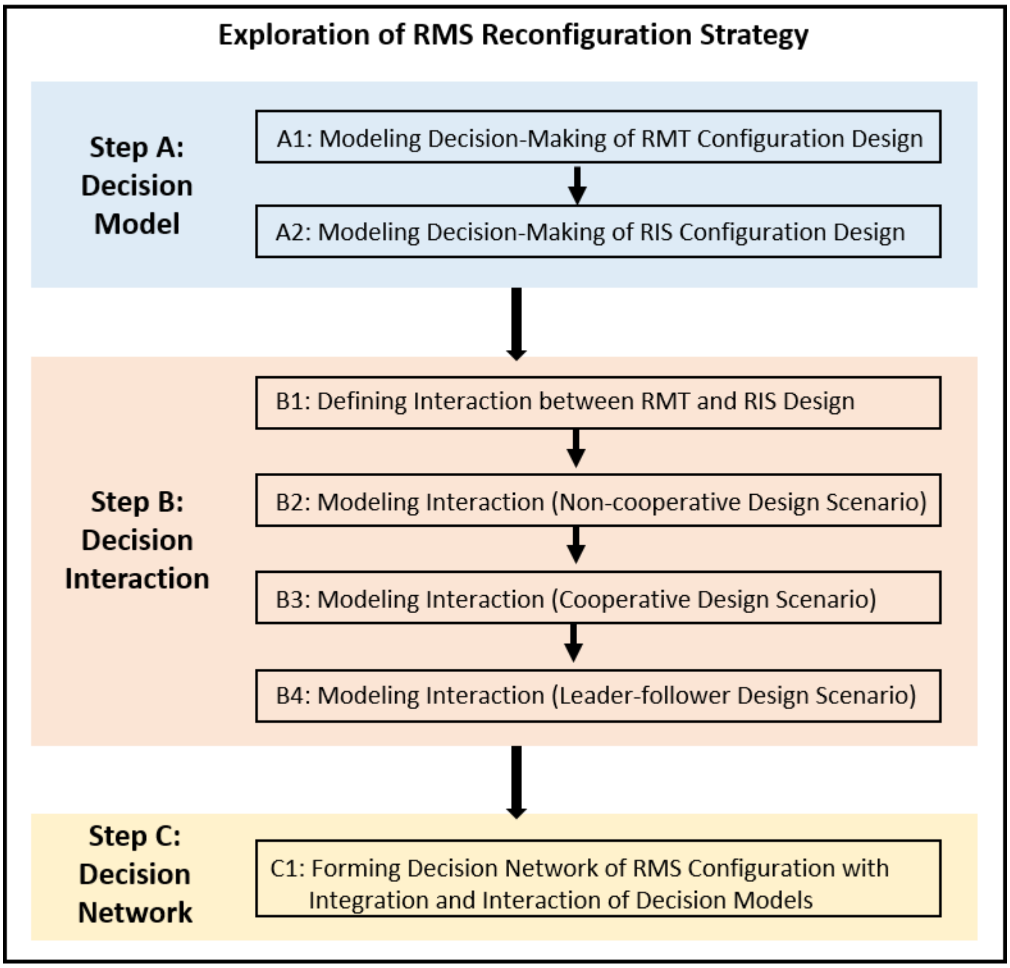



**Figure 6.9. The Proposed Specific Process to Explore the RMS Reconfiguration Strategy**

Previously mentioned problems can be solved with the proposed specific process to explore the RMS reconfiguration strategy, Figure 6.9, consisting of three steps:

***Step A. Build the Decision Models.*** The key issues of RMT and RIS configuration decision-making configuration are discussed. To manage the decision models, the decision-making models are framed according to the compromise Decision Support Problem construction.

***Step B. Describe the Decision Interaction.*** There are three types of the interactions between the decision-making models defined in Step A, weak-weak relationship, strong-strong relationship, and strong-weak relationship.

We use the corresponding models in the game theory to describe the different interactions.

***Step C. Form the Decision Network.*** According to the decision-making models and their interactions, the decision network for exploring the RMS reconfiguration strategy is presented. The core of the network is the integration of decision-making and the consideration of interactions.

### 6.3.3 CDSP-Based Model for Decision-Making in RMS Configuration Design

In this Section, the focus on the RMT and RIM configuration design in the exploration of the RMS reconfiguration strategy. Wang, et al., 2017, and Shang, et al., 2018 discuss the procedures of RMT and RIS configuration design. The main tasks of the RMT configuration design is the selection the appropriate module and its assembly relationship. Feazible solution is aimed at providing the available capability and function to satisfy the given process requirements while minimizing the cost and maximizing the reconfigurability. Thus, the variables in the RMT configuration design are the module and assembly relationships. The feasible design space is bounded by capability constraint and functionality constraint, where the RMT capability is required to match the number of operations and the functionality is required to manufacture all the operating features. In the end the final satisfied design is selected from the feasible design space, which can be reconfigured via adding, removing, or moving modules in a cost-effective and utilization-effective way. In addition, in view of the systemic exploration for RMS reconfiguration, the design process of the RMT needs to consider issues such as routing arrangements and quality inspections. Therefore, the decision-making of RMT configuration needs to take RIM's design information into account.

**Table 6.5. The cDSP Construct of the RMT Configuration Design**

| | | |
|---|---|---|
| **Given** | | |
| Processing Route | $C_p = \left\{C_{p1}, \cdots, C_{pN_{cp}}\right\}$ | Fixed |
| Operation Features | $O_{cpi} = \{O_{i1}, \cdots, O_{i6}\}$ | Fixed |
| Limited Number of Workstations | $N_s$ | Fixed |
| Module Library | $u_{ijr}$ | Fixed |
| Economic Investment | $E$ | Fixed |
| RIM Number, Position, and Sensor Quantity | $N_{IM}, P_{IM}, X$ | Flexible |
| $k^{th}$ RMT Capability and Functionality | $FCT_k, CCT_k$ | Flexible |
| $t^{th}$ RIM Capability and Functionality | $FCRIS_t, CCRIS_t$ | Flexible |
| Cost | $EMT + EIM$ | Flexible |
| Reconfigurability | $RMT$ | Flexible |
| Diagnosability | $DIM$ | Flexible |
| Initial solution of RMS configuration | $CRMS_0$ | Fixed |
| **Find** | | |
| RMT Number | $N_{MT}$ | Flexible |
| RMT Position | $P_{MT}$ | Flexible |
| $k^{th}$ RMT Module | $U_k$ | Flexible |
| $k^{th}$ RMT Assembly | $V_k$ | Flexible |
| Deviation Variable | $d_i^+, d_i^-$ | Flexible |
| **Satisfy** | | |
| Complete operational tasks | $CCT_k \geq O_{cpi}$<br>$FCT_k \geq O_{cpk}$ | |
| Provide effective detection | $FCRIS_t \geq \sum O_{cpk}$<br>$CCRIS_t \leq H(T)$ | |
| Meets the need of factory space | $N_{MT} + N_{IM} \leq N_S$<br>$P_{MT} \oplus P_{IM} = 1$ | |
| Reduce the expected cost | $E_{MT} + E_{IM} + d_1^- - d_1^+ = E$ | |
| Improve the reconfigurability | $R_{IM} + d_2^- - d_2^+ = 1$ | |
| Improve the diagnosability | $D_{IM} + d_3^- - d_3^+ = 1$ | |
| **Boundary** | | |
| Range of the RMT number | $\frac{N_{cp}}{3} \leq N_{MT} \leq N_S - 1$ | |
| Range of the module number | $1 \leq \sum u_{1j0} \leq 3$ | |
| **Minimize** | | |
| Deviation function | $MinZ = w_1 d_1^+ + w_2 d_2^- + w_3 d_3^-$ | |

On the other hand, the core of the RIS configuration design is to decide the appropriate number of RIMs and put them in the appropriate positions. The design variables considered in this matter are the RIM quantity, location, and its sensors number. The goal for this decision-making is minimizing the cost but maximizing the diagnosability while satisfying the constraint of the detection capability and functionality. The constraint of detection capability refers to the sensitivity of manufacturing errors while the detection functionality is limited to provide the detection for all RMTs. The schemes which meets the above constraints are the feasible RIS configuration design. The final solution is located through the minimization of the installation costs and the maximization of the validity and timeliness of the data. Similarly, as the RIS detection capability and functionality is matched with the RMT production capability and functionality, the RIS configuration is influenced by the RMT configuration design.

**Table 6.6. The cDSP Construct of the RIS Configuration Design**

| | | |
|---|---|---|
| **Given** | | |
| Processing Route | $C_p = \left\{C_{p1}, \cdots, C_{pN_{cp}}\right\}$ | Fixed |
| Operation Features | $O_{cpi} = \{O_{i1}, \cdots, O_{i6}\}$ | Fixed |
| Limited Number of Workstations | $N_s$ | Fixed |
| Module Library | $u_{ijr}$ | Fixed |
| Economic Investment | $E$ | Fixed |
| RIM Number, Position, and Sensor Quantity | $N_{IM}, P_{IM}, X$ | Flexible |
| $k^{th}$ RMT Capability and Functionality | $FCT_k, CCT_k$ | Flexible |
| $t^{th}$ RIM Capability and Functionality | $FCRIS_t, CCRIS_t$ | Flexible |
| Cost | $EMT + EIM$ | Flexible |
| Reconfigurability | $RMT$ | Flexible |
| Diagnosability | $DIM$ | Flexible |
| Initial solution of RMS configuration | $CRMS_0$ | Fixed |
| **Find** | | |
| RIM Number | $N_{MT}$ | Flexible |
| RIM Position | $P_{IM}$ | Flexible |
| $t^{th}$ RIM sensor | $X$ | Flexible |
| Deviation Variable | $d_i^+, d_i^-$ | Flexible |
| **Satisfy** | | |
| Complete operational tasks | $CCT_k \geq O_{cpi}$<br>$FCT_k \geq O_{cpk}$ | |
| Provide effective detection | $FCRIS_t \geq \sum O_{cpk}$<br>$CCRIS_t \leq H(T)$ | |
| Meets the need of factory space | $N_{MT} + N_{IM} \leq N_S$<br>$P_{MT} \oplus P_{IM} = I$ | |
| Reduce the expected cost | $E_{MT} + E_{IM} + d_1^- - d_1^+ = E$ | |
| Improve the reconfigurability | $R_{IM} + d_2^- - d_2^+ = 1$ | |
| Improve the diagnosability | $D_{IM} + d_3^- - d_3^+ = 1$ | |
| Boundary | | |
| Range of the RIM number | $1 \leq N_{IM} \leq N_S/2$ | |
| Range of the RIM positon | $P_{IM} = 1$ | |
| **Minimize** | | |
| Deviation function | $MinZ = w_1 d_1^+ + w_2 d_2^- + w_3 d_3^-$ | |

### 6.3.4 Game Theory-Based Model for Interactions in RMS Configuration Design

In the design process, the interactions between activities usually consists of three types: independent, sequential, and dependent relationship (Jackson, 2011). The independent activities, the relevant designers just consider their own needs and neglect other information. Conversely, the designers have to exchange the information in the dependent activities and their decision-making rely on the decision-making of other designers. The sequential activities are the special example of the dependent activities, of which the occurrence is performed in a sequential order and the decision-making of the upstream activities is the precondition of the downstream activities.

The reconfiguration of the RMS is an integration process of RMT and RIS configuration design. Besides the configuration design of RMS and RIS, the interactions between them is the important issue to be solved in the exploration of reconfiguration strategy. In this section, we use the Game Theory to describe and model the interactions. Thus, exploring the RMS reconfiguration strategy is regarded as the game. In game, the players are designers related to the RMT and RIS configuration design. Their strategic space is a suitable configuration design for each other. Due to the different interactions, we define the different game principles and the judging criteria are reconfigurability as well as diagnosability.

In RMS, the role of RMT is to provide the required processing capabilities and functionality, and to increase the reconfigurability in the configuration design process to adapt to the dynamic market. The RIS's main responsibility is to provide the efficient detection capability and functionality, and to increase the diagnosability to improve product quality. However, both the reconfigurability and the diagnosability are conflicted with the cost, where the expected investment is fixed. In order to select the configuration design of RMT and RIS, the above trade-off is solved around cost. According to the information exchange between RMT and RIS configuration design process, the exploration process is divided into the following three situations:

***Situation 1. Weak-weak interaction.*** In the process of designing and constructing the RMS, an enterprise independently separates the production and the inspection system into two projects and bids for two different design companies. The two companies are designing their own tasks without knowing for each other. At this point, the RMT configuration design and the RIS configuration design have no information flow. Any design is based on the prediction of the other party's design situation, and the design scheme is independently developed to achieve maximum reconfigurability and diagnosability.

***Situation 2. Strong-strong interaction.*** In the process of designing and building RMS, enterprises form alliances between enterprises and cooperate to complete production system and inspection system projects. In the enterprise alliance, the companies cooperate with each other according to the alliance agreement to reach a consensus on the allocation of design configuration resources, and to maximize the reconfigurability and diagnosability at the same time.

***Situation 3. Strong-weak interaction.*** The enterprise takes the lead in designing the RMS process, which itself completes the design and construction tasks of the RMS production process; outsources the inspection system project and requires its design to match its own proposed production process design. That is, RMT configuration design is the premise of RIS configuration design.

When there is weak-weak interaction between RMT and RIS configuration design, the information exchange between two decisions is difficult. In order to maximize the comprehensive performance, the non-cooperative model in game theory is chosen to explore the solution space. When there is a strong-strong interaction between RMT and RIS, the two teams will cooperate and share information. At this point, the cooperation model in game theory is selected to explore the solution space. When there is a strong-weak interaction between RMT and RIS, the design of RMT configuration precedence over the design of RIS configuration. In this case, we choose the leader-follower model in game theory to explore the solution space.

The specific procedures of the solution algorithm for the above three scenarios are as follows:

*Scenario1. Solution space exploration in weak-weak interaction (Figure 6.10)*

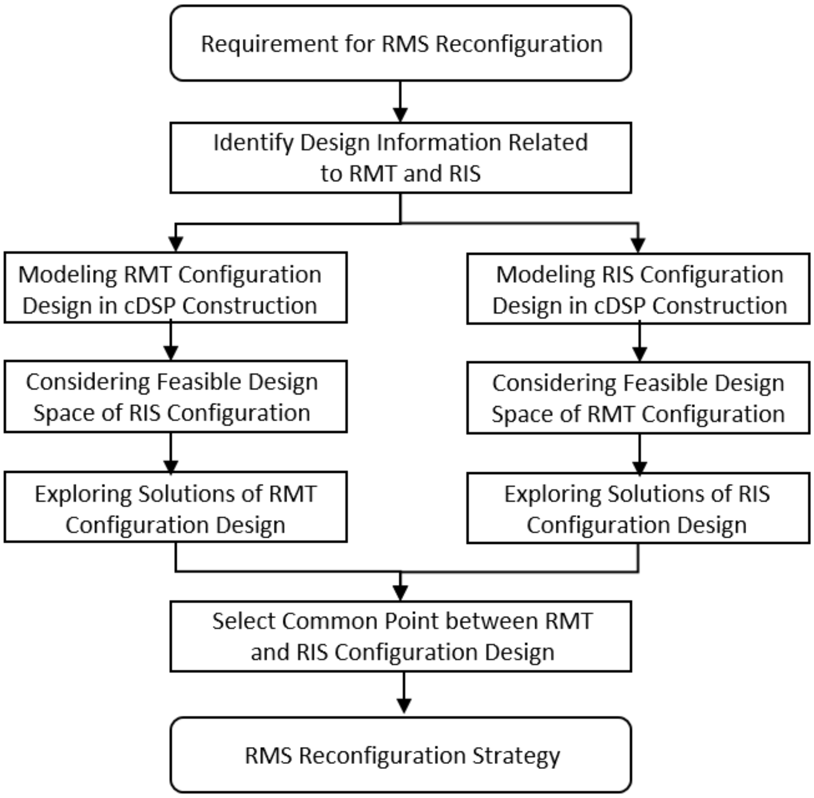



**Figure 6.10. Solution Space Exploration in Weak-Weak Interaction**

***Step 1.*** Identify the design information such as variables, constraints, and targets of RMT and RIS configuration design.

***Step 2.*** Establish the cDSP-based model for RMT and RIS configuration design according to the design information.

***Step 3.*** Take each other's feasible design space as the hypothesis parameter into the decision model. The specific parameter value is defined to solve the decision model and finally obtain the corresponding solution space.

***Step 4.*** The point selected in the intersection of the two solution spaces in Step 3 is the satisfactory solution to the RMS systemic reconfiguration strategy.

*Scenario 2. Solution space exploration in strong-strong interaction (Figure 6.11)*

***Step 1.*** Identify the design information such as variables, constraints, and targets of RMT and RIS configuration design.

***Step 2.*** Establish the cDSP-based models for RMT and RIS configuration design according to the design information.

***Step 3.*** Combine the cDSP-based models of RMT and RIS configuration design into a cDSP-based model of RMS reconfiguration design and explore the solution as the reconfiguration strategy.

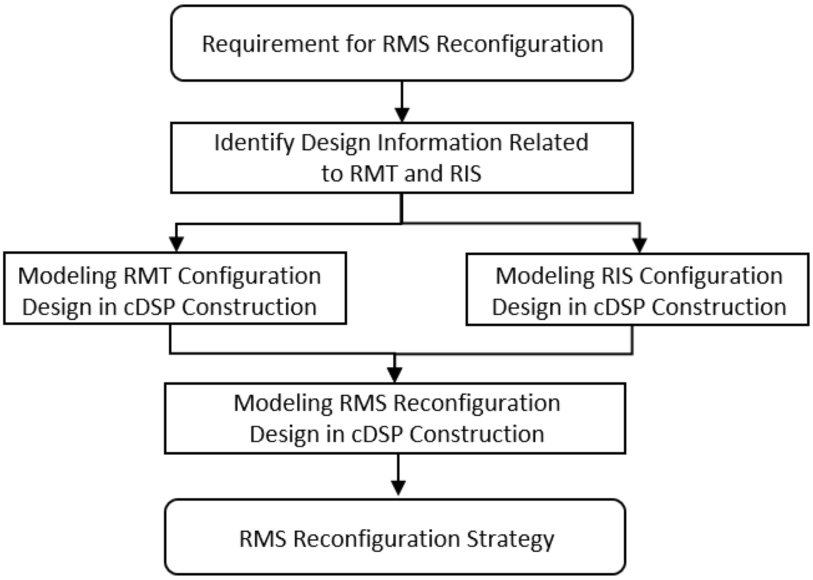



**Figure 6.11. Solution Space Exploration in Strong-Strong Interaction**

*Scenario 3. Solution space exploration in strong-weak interaction (Figure 6.12)*

***Step 1.*** Identify the design information such as variables, constraints, and targets of RMT and RIS configuration design.

***Step 2.*** Establish the cDSP-based model for RMT and RIS configuration design according to the design information.

***Step 3.*** Bring the feasible domain of RIS configuration design as a hypothesis parameter to the decision model of RMT configuration design. Then select the specific parameter values to solve the decision model, and finally obtain the corresponding solution space of the RMT configuration design.

***Step 4.*** Bring the RMT solution space of Step 3 into the decision model of the RIS configuration design to obtain the corresponding solution space of the RIS configuration design.

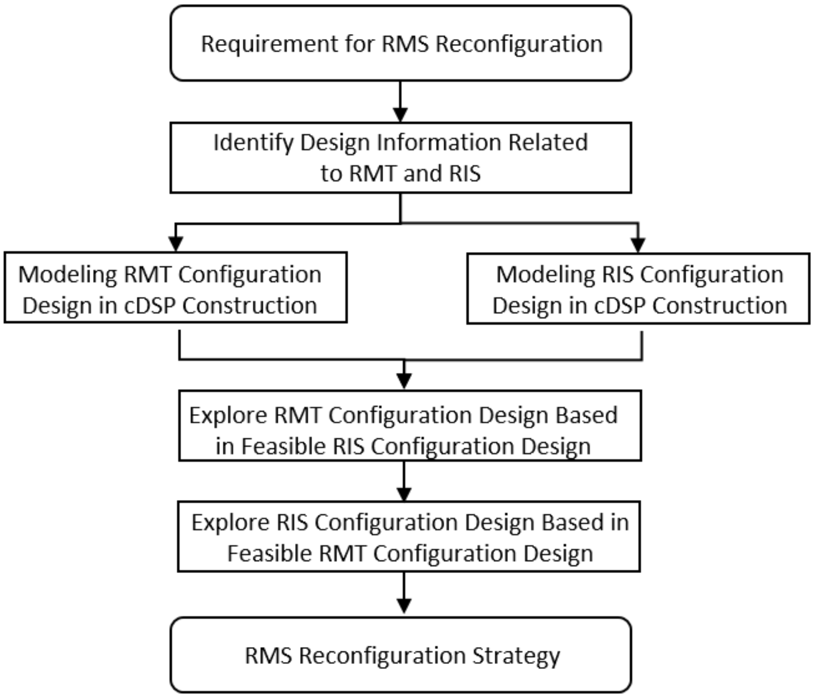



**Figure 6.12. Solution Space Exploration in Strong-Weak Interaction**

### 6.3.5 Decision Network for Exploring the RMS Reconfiguration Strategy

The reconfiguration process of RMS needs the support of a single-granularity configuration design, as well as stress on the interactive relationship between different granularity configurations. In this section, we combine the decision-making models and interaction models to construct the decision network for the support of RMS reconfiguration strategy exploration, as shown in Figure 6.13. This network lays the foundation for the dynamic management of the RMS reconfiguration.

The input of the decision network is the RMS reconfiguration requirement for the designer to formulate a systemic configuration design. This design requirement determines the static problem analysis and dynamic data input for decision networks, including design parameters, design variables, and so on. The final output of the decision model is a satisfiable RMS reconfiguration strategy that supports the designer to make the rational decisions, thereby improving the efficiency of manufacturing process.

The information needs to be preprocessed due to the diversity and complexity of the input information, Step A. By constructing a common design architecture, the relevant information of different granular configurations can be efficiently collected and analyzed. At the same time, design information is divided into design variables, design parameters, and configuration design goals. Then, according to the design architecture, the single- granularity configuration design is analyzed and explored the initial solution, Steps B and F. With the increase in the number of RMS devices, the complexity of the RMS reconfiguration increases, which increase the uncertainty of the design solution. According to the key features of different RMS granularity configuration and the corresponding performance indicators, the relationship between design variables and design parameters is defined, and a single-grain configuration design scheme is explored. When performance indicators or design goals change, it requires a re-exploration of space exploration. A single-granularity configuration design scheme is used as the initial solution to explore the systemic reconfiguration strategy. Considering the interactions between different granularities configuration design, the exploration of RMS reconfiguration strategy, Steps C and F, is established. The solution of the cDSP-based model is to provide the most satisfactory scheme. Its evaluation index mainly focuses on satisfying customer preferences and solving the trade-off of multiple objectives through weights setting. The weights can be derived from system simulation, Step D, or application scenario analysis, Step E. The weights is also used to analyze the sensitivity of the design plan to dynamic demand changes, and further promote the designer's understanding of the RMS reconfiguration behavior. Finally, the designers evaluate the satisfactory design schemes, which is used as the initial value of the next stage to carry out multiple iterations of the design process to promote the dynamic management of RMS reconfiguration.

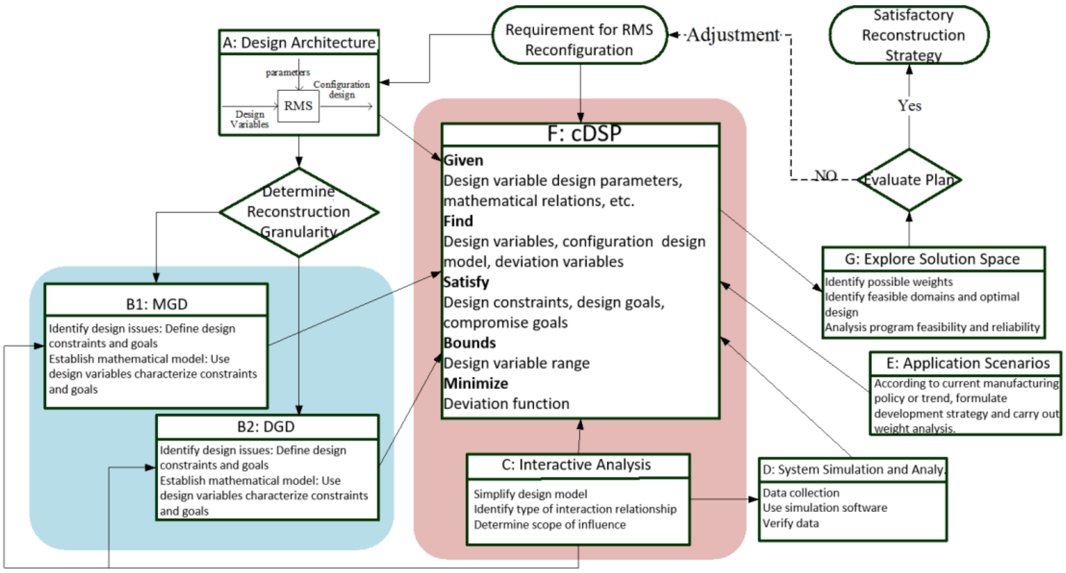



**Figure 6.13. Decision Network for Exploring the RMS Reconfiguration Strategy**

## 6.4 Results and Discussion

In this section, we are discussing the application of Reconfigurable Machine Tool (RMT), Reconfigurable Inspection System (RIS), and Reconfigurable Manufacture System (RMS) Configuration Design. RMT configuration design is verified with transmission box production as a test example, Section 6.5.1. RIS configuration design is verified with headstock test example, Section 6.5.2. RMS configuration design is verified with engine cylinder block test example, Section 6.5.3.

### 6.4.1 Application of Reconfigurable Machine Tool (RMT) Configuration Design

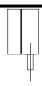
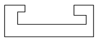
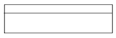
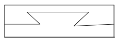
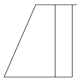
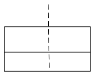
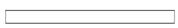
A transmission box in a vehicle plays a supportive and connective role in the entire reducer assembly. The quality of the box directly affects not only the accuracy of the location of parts (e.g., shafts and gears) but also the life and performance of the reducer. This box is a typical box-type part and the main operations of manufacturing this part include a high-precision plane, bearing holes, screw holes, etc. Due to application demands in the field and an unstable demand/supply relationship, the multi-transmission boxes manufacturing process will face product variance or fluctuating order demand. A complex market environment forces the manufacturing system to be equipped with RMTs to have the ability of converting functionality and scaling the capability.

*Three Design Scenarios for Transmission Box Production*

According to the functions of modules, motion and support, the simplified module library for the design RMT in the example is shown in Table 6.7. The details of module division are discussed the previous literature (Moon and Kota, 2002; Chen, et al., 2005). To build the configuration tree, the premise is to define the mappings between the basic modules and the nodes listed in Table 6.2. When the function is used as the mapping standard, the one-to-one relationship between modules and nodes is revealed in Figure 6.14, which also shows the number of the node and the module.

The motivation for reconfiguration is to maintain and update the manufacturing performance of RMTs. First, certain RMTs may not be capable of the needed accuracy or even be broken, so some of the modules in the configuration require the replacement. Second, the product variants would require previously unavailable functions. The RMT need to add some new modules (e.g., slides or columns) to enable new functionality or remove some existing modules to reduce redundancy.

**Table 6.7. RMT Basic Modules and the Corresponding Costs**

| # | Module Name | Simplified Module | Fixed Cost | Assembly Cost |
|---|---|---|---|---|
| 1 | Spindle head |  | 2000 | 1000 |
| 2 | Fixture |  | 1500 | 800 |
| 3 | Slider |  | 200 | 100 |
| 4 | Cross-slider |  | 200 | 100 |
| 5 | Column |  | 600 | 200 |
| 6 | Rotary table |  | 450 | 150 |
| 7 | Base |  | 800 | 200 |

Third, demand fluctuation can result in the need to scale the capability. If the capability of the RMT needs to be increased the RMT adds spindle heads to realize additional operations in the same configuration, or the RMT requires removal of spindle heads to reduce redundancy. Hence, the remaining sections analyze the RMT configuration design in detail for three different scenarios:

- *Scenario 1.* In the pre-planning phase, an RMT configuration is designed only around a given set of operational requirements;
- *Scenario 2.* The features of the operations change but the quantity remains the same. A new RMT configuration is designed on basis of the configuration scheme in the first case; and
- *Scenario 3.* The quantity of the operations changes but the features remain the same. Another RMT configuration is designed on basis of the configuration scheme in the second case.

In all scenarios, there are two phases in the RMT configuration design process. The first is to generate feasible configuration trees with design constraints of capability and functionality. The second is to select the most satisfactory configuration tree with the design goals of cost and reconfigurability. According to the selected design scheme of configuration trees, the corresponding three-dimensional figures of RMT configuration are printed via the relationship of modules and nodes.

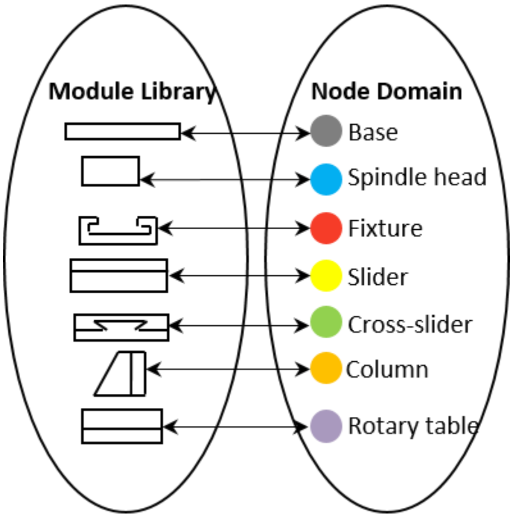



**Figure 6.14. Mappings between the Module Library and the Node Domain**

***RMT Configuration Design and Decision-Making for Fixed Operation Requirements (Scenario 1).*** The transmission box type (Level 2) is in the pre-planning phase shown in Figure 6.15. The operational requirement for a specified RMT is to process the upper surface, rectangle in the Figure 6.15. As the RMT processes the upper surface the operational requirement contains one operation (n = 1). This operation requires relative motions between tools and workpieces along the X-, Y-, and Z- axes.

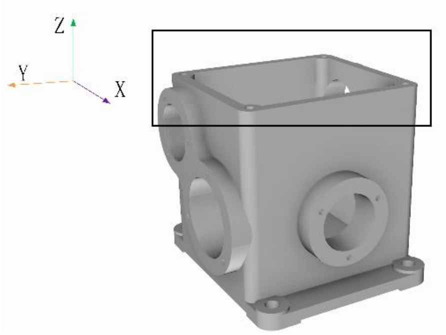


**Figure 6.15. Three-Dimensional Model of Level-2 Transmission Box in Scenario**

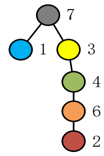
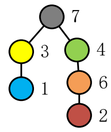
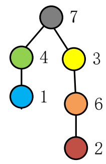
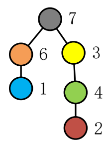
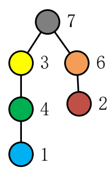
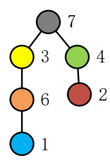
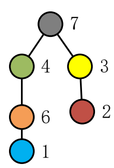
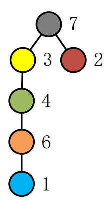
*Generation of Feasible RMT Configuration Trees for Scenario 1*

Consistent with the operational requirement, the constraint model of capability and functionality is as follows:

$$\begin{cases} \sum_{j \in N} f_2(x_{1j1}) = 1 \\ \begin{cases} t_{1r} \oplus h_{1r} = 1 \ \ (r = 1, 2, 3) \\ t_{1r} \oplus h_{1r} = 0 \ \ (r = 4, 5, 6) \end{cases} \end{cases} \tag{6.43}$$

The node set that meets the operation requirements is determined by solving the constraint model in Equation 6.43. The set involves six nodes type: the spindle head node, slider node, cross-slider node, column node, fixture node, and base node. Except for the base node, spindle head node, and fixture node, we randomly assign the directional nodes to the tool-side and workpiece-side branches in the assembly process, Section 6.2.2. As a result, there are eight feasible RMT configuration trees formed, Table 6.8.

## Table 6.8. The Feasible Configuration Trees Designed for Scenario 1

| Scheme | Degree of Freedom | | Configuration Tree | Mathematical Description |
|---|---|---|---|---|
| | Tool-side branch | Workpiece -side branch | | |
| 1 | None | X, Y, Z |  | $\boldsymbol{C_1} = \left\{\begin{matrix} x_{710}, x_{110}, x_{311}, x_{411}, x_{511}, x_{211}, \\ \langle x_{710}, x_{110}\rangle, \langle x_{710}, x_{311}\rangle, \langle x_{311}, x_{411}\rangle, \\ \langle x_{411}, x_{511}\rangle, \langle x_{511}, x_{211}\rangle \end{matrix}\right\}$ |
| 2 | X | Y, Z |  | $\boldsymbol{C_2} = \left\{\begin{matrix} x_{710}, x_{110}, x_{310}, x_{211}, x_{411}, x_{511}, \\ \langle x_{710}, x_{310}\rangle, \langle x_{310}, x_{110}\rangle, \langle x_{710}, x_{411}\rangle, \\ \langle x_{411}, x_{511}\rangle, \langle x_{511}, x_{211}\rangle \end{matrix}\right\}$ |
| 3 | Y | X, Z |  | $\boldsymbol{C_3} = \left\{\begin{matrix} x_{710}, x_{410}, x_{110}, x_{311}, x_{511}, x_{211}, \\ \langle x_{710}, x_{410}\rangle, \langle x_{410}, x_{110}\rangle, \langle x_{710}, x_{311}\rangle, \\ \langle x_{311}, x_{511}\rangle, \langle x_{511}, x_{211}\rangle \end{matrix}\right\}$ |
| 4 | Z | X, Y |  | $\boldsymbol{C_4} = \left\{\begin{matrix} x_{710}, x_{510}, x_{110}, x_{311}, x_{411}, x_{211}, \\ \langle x_{710}, x_{510}\rangle, \langle x_{510}, x_{110}\rangle, \langle x_{710}, x_{311}\rangle, \\ \langle x_{311}, x_{411}\rangle, \langle x_{411}, x_{211}\rangle \end{matrix}\right\}$ |
| 5 | X, Y | Z |  | $\boldsymbol{C_5} = \left\{\begin{matrix} x_{710}, x_{310}, x_{410}, x_{110}, x_{511}, x_{211}, \\ \langle x_{710}, x_{310}\rangle, \langle x_{310}, x_{410}\rangle, \langle x_{410}, x_{110}\rangle, \\ \langle x_{710}, x_{511}\rangle, \langle x_{511}, x_{211}\rangle \end{matrix}\right\}$ |
| 6 | X, Z | Y |  | $\boldsymbol{C_6} = \left\{\begin{matrix} x_{710}, x_{310}, x_{510}, x_{110}, x_{411}, x_{211}, \\ \langle x_{710}, x_{310}\rangle, \langle x_{310}, x_{510}\rangle, \langle x_{510}, x_{110}\rangle, \\ \langle x_{710}, x_{411}\rangle, \langle x_{411}, x_{211}\rangle \end{matrix}\right\}$ |
| 7 | Y, Z | X |  | $\boldsymbol{C_7} = \left\{\begin{matrix} x_{710}, x_{410}, x_{510}, x_{110}, x_{311}, x_{211}, \\ \langle x_{710}, x_{410}\rangle, \langle x_{410}, x_{510}\rangle, \langle x_{510}, x_{110}\rangle, \\ \langle x_{710}, x_{311}\rangle, \langle x_{311}, x_{211}\rangle \end{matrix}\right\}$ |
| 8 | X, Y, Z | None |  | $\boldsymbol{C_8} = \left\{\begin{matrix} x_{710}, x_{310}, x_{410}, x_{510}, x_{110}, x_{211}, \\ \langle x_{710}, x_{310}\rangle, \langle x_{310}, x_{410}\rangle, \langle x_{410}, x_{510}\rangle, \\ \langle x_{510}, x_{110}\rangle, \langle x_{710}, x_{211}\rangle \end{matrix}\right\}$ |

1.Spindle Head; 2. Fixture; 3. Slider; 4. Cross-Slider; 5. Column; 6. Rotatory table; 7. Base.

***Decision-making for the Most Satisfactory RMT Configuration Tree in Scenario 1.*** After generating the feasible design space, the decision indicators such as fixed cost *g(u),* assembly cost *q(u),* utilization rate *UCT* and similarity rate *PCT* are calculated using Equations 6.24 – 6.26. The evaluation results are shown in Table 6.9. The configuration design process occurs in the pre-production phase in which there are no previous configurations for comparison; therefore, the utilization rates of all RMT configuration trees are 1. Further, the deviations of cost and reconfigurability are processed using Equations 6.27 and 6.28, presented in Table 6.10. The weights of reconfigurability and cost are set to be 0.8 and 0.2 because the reconfigurability is more important than the cost in the initial RMT design phase. Finally, the deviation values and weight values are substituted into Equation 6.29 to obtain the objective function value. The deviation values and objective function values of all schemes are listed in Table 6.10. Based on the selective objective function values, a trend chart illustrating the performance of the RMT configuration schemes is presented in Figure 6.16.

**Table 6.9. RMT Configuration Tree Decision Indicators in Scenario 1**

| Index / Scheme | *g(u)* | *q(u)* | *ECT* | *UCT* | *PCT* | *RCT* |
|---|---|---|---|---|---|---|
| 1 | 5300 | 3000 | 8300 | 1 | 0.133 | 1.133 |
| 2 | 5300 | 3000 | 8300 | 1 | 0.800 | 1.800 |
| 3 | 5300 | 3000 | 8300 | 1 | 0.400 | 1.400 |
| 4 | 5300 | 3000 | 8300 | 1 | 0.400 | 1.400 |
| 5 | 5300 | 3000 | 8300 | 1 | 0.400 | 1.400 |
| 6 | 5300 | 3000 | 8300 | 1 | 0.400 | 1.400 |
| 7 | 5300 | 3000 | 8300 | 1 | 0.800 | 1.800 |
| 8 | 5300 | 3000 | 8300 | 1 | 0.133 | 1.133 |

**Table 6.10. Selected Objective Function Values of RMT Configurations Tree in Scenario 1**

| Index / Scheme | $d_1$ | $d_2$ | $I$ |
|---|---|---|---|
| 1 | 0 | 0.3704 | 0.2963 |
| 2 | 0 | 0 | 0 |
| 3 | 0 | 0.2222 | 0.1778 |
| 4 | 0 | 0.2222 | 0.1778 |
| 5 | 0 | 0.2222 | 0.1778 |
| 6 | 0 | 0.2222 | 0.1778 |
| 7 | 0 | 0 | 0 |
| 8 | 0 | 0.3704 | 0.2963 |

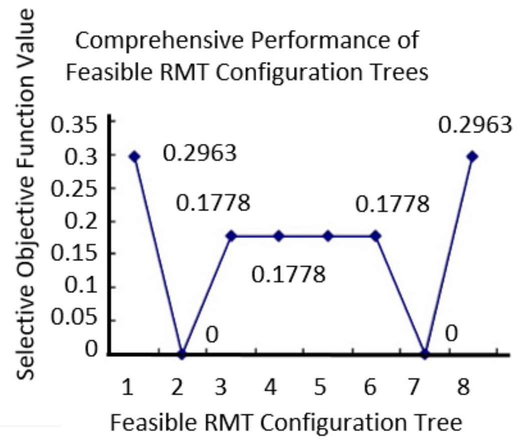



**Figure 6.16. Performance of Feasible RMT Configuration**

The decision objective function $I$ values of Schemes 2 and 7 are the smallest. These schemes are relatively close to the ideal solution, which is expected to minimize the cost yet maximize the reconfigurability. As a result, the two satisfactory RMT configuration trees are selected. This result is due to the lack of a reconfiguration process, i.e., there is no need to design on the basis of previous configurations. Hence, some of indices related to reconfiguration, such as assembly cost and utilization rate, are useless for the design decision. Based on production experience, when the workpieces are large and difficult to move, workpiece-related configurations must have as few DOFs as possible; thus, the number of DOFs in the tool-related configuration should be increased. Because of the dimensions of the Level 2 transmission box, Scheme 2 is chosen as the most satisfactory RMT configuration tree in Scenario 1, Figure 6.17.

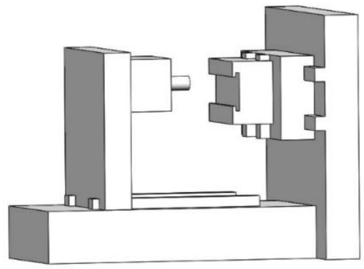


**Figure 6.17. Most Satisfactory RMT Configuration for Scenario 1**

***RMT Configuration Design and Decision-Making for Operational Feature Changes (Scenario 2).*** Because of the fluctuations in market demands, the type or batch size of workpieces in new orders may change. Therefore, there is a need to re-plan the processing route, which would result in reconfiguring some of the RMTs. In this section, the proposed method is applied for redesigning an RMT configuration when there are changes in operational features.

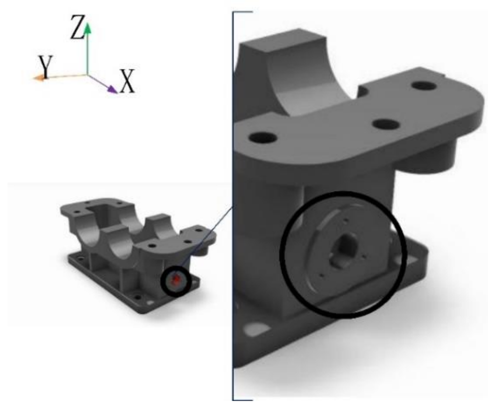


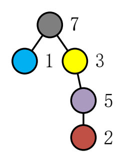
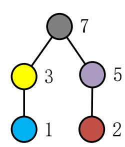
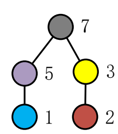
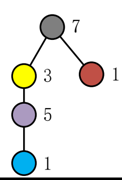

**Figure 6.18. Three-Dimensional Model of Level-2 Transmission Box in Scenario 2**

The desired type of transmission box for new orders is illustrated in Figure 6.18. This requires the RMT to process the side whole, circle in Figure 6.18. The operational set of this RMT contains only one operation ($n$ = 1). Using the three-dimensional coordinate system the operation feature is accomplished by the relative motions between tools and workpieces along the X- and A- axes. Compared with the operational requirements, Section 6.2.1, the number of machining operations required in the new process remains the same, but the operation itself is different. Hence, it is necessary for the RMT to be reconfigured from the original configuration.

***Generation of Feasible RMT Configuration Trees for Scenario 2.*** In the same manner as Section 6.2.1, the constraint model for the node set of decisions in this process is obtained as follows:

$$\begin{cases} \sum_{j \in N} f_2(x_{1j1}) = 1 \\ \begin{cases} t_{1q} \oplus h_{1q} = 1 \ \ (q = 1, 4) \\ t_{1q} \oplus h_{1q} = 0 \ \ (q = 2, 3, 5, 6) \end{cases} \end{cases} \tag{6.44}$$

**Table 6.11. The Feasible RMT Configuration Trees Designed in Scenario 2**

| Scheme | Degree of Freedom | | Configuration Tree | Mathematical Description |
|---|---|---|---|---|
| | Tool-side branch | Workpiece-side branch | | |
| 1 | None | X, A |   | $C_1 = \left\{ \begin{matrix} x_{710}, x_{110}, x_{211}, x_{311}, x_{611}, \\ \langle x_{710}, x_{110} \rangle, \langle x_{710}, x_{311} \rangle, \langle x_{311}, x_{611} \rangle, \\ \langle x_{611}, x_{211} \rangle \end{matrix} \right\}$ |
| 2 | X | A |   | $C_2 = \left\{ \begin{matrix} x_{710}, x_{110}, x_{310}, x_{211}, x_{711}, \\ \langle x_{710}, x_{310} \rangle, \langle x_{310}, x_{110} \rangle, \langle x_{710}, x_{611} \rangle, \\ \langle x_{611}, x_{211} \rangle \end{matrix} \right\}$ |
| 3 | A | X |   | $C_3 = \left\{ \begin{matrix} x_{710}, x_{610}, x_{110}, x_{311}, x_{211}, \\ \langle x_{710}, x_{610} \rangle, \langle x_{610}, x_{110} \rangle, \langle x_{710}, x_{311} \rangle, \\ \langle x_{311}, x_{211} \rangle \end{matrix} \right\}$ |
| 4 | X, A | None |   | $C_3 = \left\{ \begin{matrix} x_{710}, x_{110}, x_{310}, x_{610}, x_{211}, \\ \langle x_{710}, x_{310} \rangle, \langle x_{310}, x_{610} \rangle, \langle x_{610}, x_{110} \rangle, \\ \langle x_{710}, x_{211} \rangle \end{matrix} \right\}$ |

1.Spindle Head; 2. Fixture; 3. Slider; 4. Cross-Slider; 5. Column; 6. Rotatory table; 7. Base.

The node set for this process consists of the spindle head node, the base node, the fixture node, the slider node, and the rotary table node. These nodes are formed into four feasible RMT configuration trees, Table 6.11.

***Decision-making for the Most Satisfactory RMT Configuration Tree in Scenario 2.*** The values of decision indices of the feasible configuration trees in Scenario 2 are presented in Table 6.12. In the development phase, the enterprises tend to expand their market share. Hence, the manufacturing process is required to be both reconfigurable and cost-effective, where reconfigurability is as important as the cost in Scenario 2, assigned weights of 0.5. The deviation values and decision function values of each scheme are presented in Table 6.13, while a chart of the performance of RMT configuration schemes is shown in Figure 6.19.

**Table 6.12. RMT Configuration Tree Decision Indicators in Scenario 2**

| Index / Scheme | *g(u)* | *q(u)* | *ECT* | *UCT* | *PCT* | *RCT* |
|---|---|---|---|---|---|---|
| 1 | 450 | 6100 | 11850 | 0 | 0.0667 | 0.0667 |
| 2 | 450 | 3200 | 8950 | 0.5 | 0.600 | 1.1000 |
| 3 | 450 | 6100 | 11850 | 0 | 0.600 | 0.6000 |
| 4 | 450 | 5400 | 11150 | 0.25 | 0.0667 | 0.3167 |

**Table 6.13. Selection Objective Function Values of RMT Configuration Trees in Scenario 2**

| Index / Scheme | $d_1$ | $d_2$ | *I* |
|---|---|---|---|
| 1 | 0.2447 | 0.9394 | 0.5921 |
| 2 | 0 | 0 | 0 |
| 3 | 0.2447 | 0.4545 | 0.7121 |
| 4 | 0.1973 | 0.7121 | 0.4547 |

The value of function *I* of Scheme 2 is the smallest, Figure 6.19. Scheme 2 has a smaller deviation from the ideal solution; therefore selected as the most satisfactory RMT configuration tree. Accordingly, the RMT configuration based on the inverse mapping between the module library and the node library is presented in Figure 6.20.

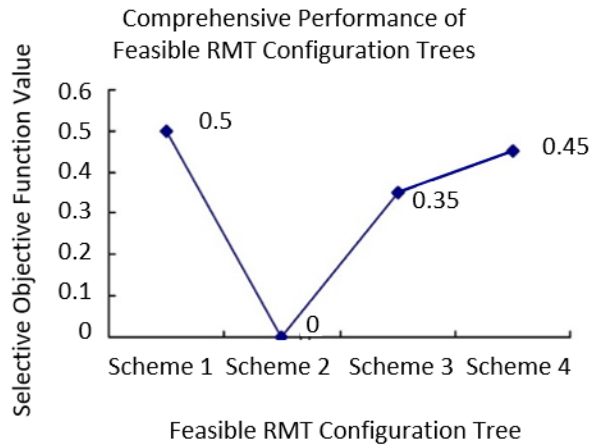



**Figure 6.19. Performance of Feasible RMT Configuration Trees for Scenario 2**

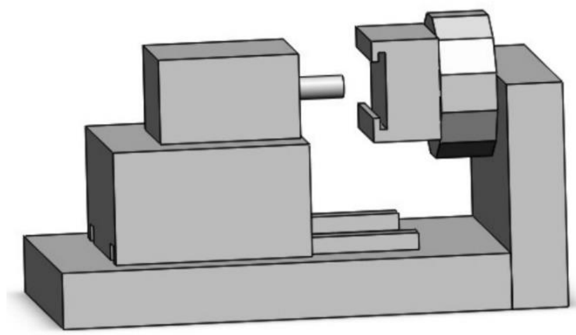


**Figure 6.20. The Most Satisfactory RMT Configuration for Scenario 2**

***RMT Configuration Design and Decision-Making for Machining Operation Quantity Changes (Scenario 3).*** In Scenario 3, the proposed method is applied to a situation in which the product quantity changes. When the batch of transmission boxes increases in a new production order, multiple operations need to be combined to guarantee a timely delivery. Consequently, the RMT is required to process both the side holes and the large upper-surface holes shown in Figure 6.21. The number of operations changes to 2 (n = 2). The features of the first operations are accomplished by the relative motions between the tools and workpieces along the X- and A- axes, and the second along the X-, Y-, and B- axes. Compared with the process described in Scenario 2, the quantity of operations increases. Consequently, the RMT, Figure 6.20, cannot fulfill the operational requirements. It is necessary for the RMT to be reconfigured based on the second configuration.

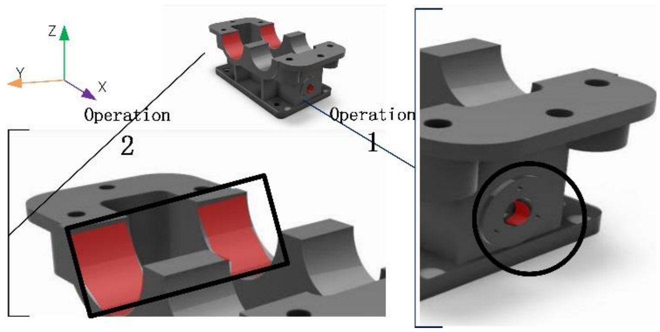



**Figure 6.21. Three-Dimensional Model of Level-2 Transmission Box in Scenario 3**

***Generation of Feasible RMT Configuration Trees.*** The constraint model for the node set decision of this process, presented in Equation 6.45, and three feasible RMT configuration trees are formed, Table 6.16.

$$\begin{cases} \sum_{j \in N} f_2(x_{1j1}) = 2 \\ \begin{cases} t_{1r} \oplus h_{1r} = 1 \ (r = 1, 4) \\ t_{1r} \oplus h_{1r} = 0 \ (q = 2, 3, 5, 6) \\ t_{2r} \oplus h_{2r} = 1 \ (r = 1, 2, 3, 6) \\ t_{2r} \oplus h_{2r} = 0 \ (r = 4, 5) \end{cases} \end{cases} \tag{6.45}$$

***Decision-making for the Most Satisfactory RMT Configuration Tree in Scenario 3.*** The values of decision indices of the feasible configuration trees are presented in Table 6.14. In this design, the weights of cost and reconfigurability are also equal to 0.5. The deviation values and decision function values of each scheme, presented in Table 6.15, while a chart of the performance of the RMT configuration schemes is shown in Figure 6.22.

**Table 6.14. RMT Configuration Decision Indicators for Scenario 3**

| Index / Scheme | *g(u)* | *q(u)* | *ECT* | *UCT* | *PCT* | *RCT* |
|---|---|---|---|---|---|---|
| 1 | 3050 | 8050 | 11100 | 0.25 | 0.1333 | 0.3833 |
| 2 | 2850 | 8750 | 11600 | 0 | 0.7333 | 0.7333 |
| 3 | 3250 | 8150 | 11400 | 0.25 | 0.4000 | 0.6500 |

The value of decision function *I* in scheme 2 is the smallest, Figure 6.22. Scheme 3 is closer to the ideal solution, which has greatly balanced cost and reconfigurability. Scheme 3 is therefore chosen as the most satisfactory RMT configuration tree. The RMT configuration based on the inverse mapping between the module library and the node library is presented in Figure 6.23.

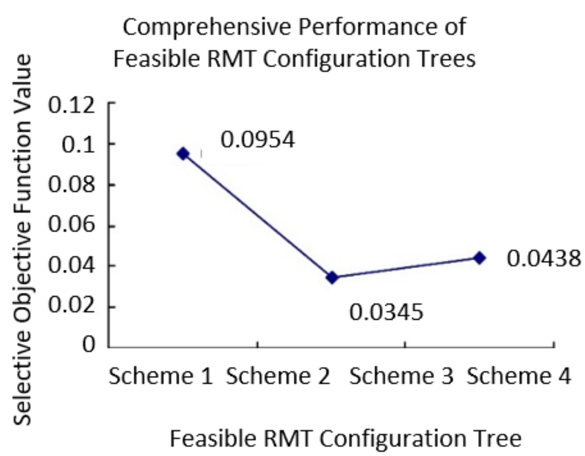



**Figure 6.22. Performance Configuration Schemes for Changes in Quantity**

**Table 6.15. Selective Objective Function Values of RMT Configuration Trees for Scenario 3**

| Index / Scheme | $d_1$ | $d_2$ | *I* |
|---|---|---|---|
| 1 | 0 | 0.4773 | 0.0954 |
| 2 | 0.0431 | 0 | 0.0345 |
| 3 | 0.0263 | 0.1136 | 0.0438 |

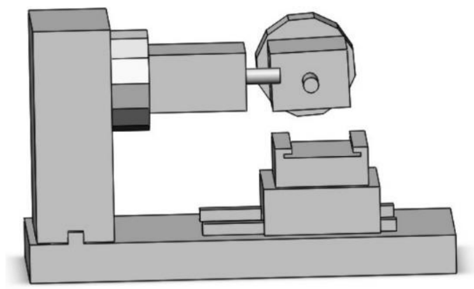
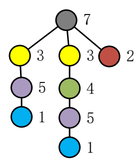
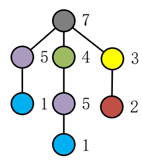
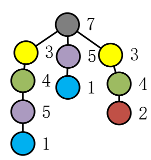


**Figure 6.23. Most Satisfactory RMT Configuration for Scenario 3**

**Table 6.16. Feasible RMT Configuration Tree Schemes in Scenario 3**

| Scheme | Degree of Freedom: Tool-side branch | Degree of Freedom: Tool-side branch | Degree of Freedom: Workpiece-side branch | Configuration Tree | Mathematical Description |
|---|---|---|---|---|---|
| 1 | X, A | X, Y, B | None |  | $\boldsymbol{C_1} = \left\{ \begin{matrix} x_{710}, x_{310}, x_{320}, x_{410}, x_{610}, x_{620}, x_{110}, \\ x_{120}, x_{211}, \langle x_{710}, x_{310} \rangle, \langle x_{310}, x_{410} \rangle \\ \langle x_{410}, x_{610} \rangle, \langle x_{610}, x_{110} \rangle, \langle x_{710}, x_{320} \rangle, \\ \langle x_{320}, x_{620} \rangle, \langle x_{620}, x_{120} \rangle, \langle x_{710}, x_{211} \rangle \end{matrix} \right\}$ |
| 2 | A | Y, B | X |  | $\boldsymbol{C_2} = \left\{ \begin{matrix} x_{710}, x_{410}, x_{610}, x_{620}, x_{110}, x_{120}, x_{311}, \\ x_{211}, \langle x_{710}, x_{410} \rangle, \langle x_{410}, x_{610} \rangle \\ \langle x_{610}, x_{110} \rangle, \langle x_{710}, x_{620} \rangle, \langle x_{620}, x_{120} \rangle, \\ \langle x_{710}, x_{311} \rangle, \langle x_{311}, x_{211} \rangle \end{matrix} \right\}$ |
| 3 | Y, X, A | B | X, Y |  | $\boldsymbol{C_3} = \left\{ \begin{matrix} x_{710}, x_{310}, x_{410}, x_{610}, x_{620}, x_{110}, x_{120}, \\ x_{321}, x_{421}, x_{211} \langle x_{710}, x_{610} \rangle, \\ \langle x_{610}, x_{110} \rangle, \langle x_{710}, x_{310} \rangle, \langle x_{310}, x_{410} \rangle, \\ \langle x_{410}, x_{120} \rangle, \langle x_{710}, x_{321} \rangle, \langle x_{321}, x_{421} \rangle, \\ \langle x_{421}, x_{221} \rangle \end{matrix} \right\}$ |

1.Spindle Head; 2. Fixture; 3. Slider; 4. Cross-Slider; 5. Column; 6. Rotatory table; 7. Base.

### 6.4.2 Application of RIS Configuration Design

The headstock is an important part of the lathe, which is usually used to lay out the machine tool spindle, its drive parts and the corresponding additional mechanisms. The spindle box is the basic components of the headstock, which machine the shaft, sleeve, gear, etc., as a whole, to ensure that the correct position between them. Furthermore, the processing quality of the box directly affects the accuracy, performance, and life of the machine. The method is described and verified based on the lathe spindle, and the mentioned part of the process of the spindle housing is presented in the Table 6.17.

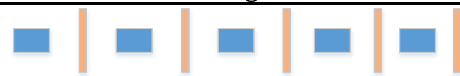
**Table 6.17. The Process Requirement Example**

| Num | Processing Surface | Datum Surface |
|---|---|---|
| 1 | M | R |
| 2 | N | R |
| 3 | Slide | R |
| 4 | P | M, N |
| 5 | Q | M, N |

Facing the production issues, the enterprise would establish an efficient detecting system and ensure the product quality. Currently, there are N = 5 stations in the manufacturing process and the error is required to be detected up to 3 stations. According to constrains models of RIS configuration design, Equation 6.46, which is for the perspective of detection capability and detection functionality, it is calculated that there are at least 14 sensors in the RIS and the distance from all of the processes to their respective detectors is no more than 40. According to the permutations and combinations, a total of 13 feasible design solutions are formed, presented in Table 6.18.

$$\begin{cases} \text{FCRIS} \geq \sum_{i=1}^{5} \sum_{j=1}^{7} H(cp_i, f_j) \times \left( \sum_{k=1, k \neq j}^{5} G(f_k) + 1 \right) = 14 \\ CCRIS \leq \dfrac{D(3) \times INT\left(\frac{5}{3}\right) + D\left(5 - 3 \times INT\left(\frac{5}{3}\right)\right)}{D(5)} = 0.4 \\ 1 \leq M \leq 5 \end{cases} \tag{6.46}$$

**Table 6.18. The Design Scheme of RIS Configuration**

| # | RIS Configuration | Model |
|---|---|---|
| 1 |  | $\boldsymbol{CRIS_1} = \{(\mathbf{1},\mathbf{2}),(\mathbf{2},\mathbf{2}),(\mathbf{3},\mathbf{2}),(\mathbf{4},\mathbf{3}),(\mathbf{5},\mathbf{3})\}$ |
| 2 |  | $\boldsymbol{CRIS_2} = \{(\mathbf{1},\mathbf{2}),(\mathbf{3},\mathbf{3}),(\mathbf{4},\mathbf{3}),(\mathbf{5},\mathbf{3})\}$ |
| 3 |  | $\boldsymbol{CRIS_3} = \{(\mathbf{1},\mathbf{2}),(\mathbf{2},\mathbf{2}),(\mathbf{4},\mathbf{5}),(\mathbf{5},\mathbf{3})\}$ |
| 4 |  | $\boldsymbol{CRIS_4} = \{(\mathbf{1},\mathbf{2}),(\mathbf{2},\mathbf{2}),(\mathbf{3},\mathbf{2}),(\mathbf{5},\mathbf{4})\}$ |
| 5 |  | $\boldsymbol{CRIS_5} = \{(\mathbf{2},\mathbf{2}),(\mathbf{3},\mathbf{2}),(\mathbf{4},\mathbf{3}),(\mathbf{5},\mathbf{3})\}$ |
| 6 |  | $\boldsymbol{CRIS_6} = \{(\mathbf{1},\mathbf{2}),(\mathbf{4},\mathbf{5}),(\mathbf{5},\mathbf{3})\}$ |
| 7 |  | $\boldsymbol{CRIS_7} = \{(\mathbf{1},\mathbf{2}),(\mathbf{3},\mathbf{3}),(\mathbf{5},\mathbf{4})\}$ |
| 8 |  | $\boldsymbol{CRIS_8} = \{(\mathbf{1},\mathbf{2}),(\mathbf{2},\mathbf{2}),(\mathbf{5},\mathbf{6})\}$ |
| 9 |  | $\boldsymbol{CRIS_9} = \{(\mathbf{3},\mathbf{4}),(\mathbf{4},\mathbf{3}),(\mathbf{5},\mathbf{3})\}$ |
| 10 |  | $\boldsymbol{CRIS_{10}} = \{(\mathbf{2},\mathbf{3}),(\mathbf{4},\mathbf{5}),(\mathbf{5},\mathbf{3})\}$ |
| 11 |  | $CRIS_{11} = \{(2,3),(3,2),(5,4)\}$ |
| 12 |  | $\boldsymbol{CRIS_{12}} = \{(\mathbf{2},\mathbf{3}),(\mathbf{5},\mathbf{6})\}$ |
| 13 |  | $\boldsymbol{CRIS_{13}} = \{(\mathbf{3},\mathbf{4}),(\mathbf{5},\mathbf{4})\}$ |

For each of the RIS feasible configuration designs described above, the cost and diagnosability decision index values are further calculated, Table 6.19. The reliability of sensor is 0.9, the cost of installing one RIM averaged 10,000 and the cost of one sensor averaged 1,000. The amount of deviation of cost and diagnosability is obtained by processing the data in the Table 6.19. The diagnosability and the cost weight are 0.5, respectively. Finally, the target function value is obtained by combining the deviation value and the weight value, and the variation tendency diagram is presented in Figure 6.24.

**Table 6.19. The Index Data of RIS Design**

| Index | Solution 1 | Solution 2 | Solution 3 | Solution 4 | Solution 5 |
|---|---|---|---|---|---|
| *ECRIS* | 6.2*10$^3$ | 5.1*10$^3$ | 5.2*10$^3$ | 5.0*10$^3$ | 5.0*10$^3$ |
| *XCRIS* | 0.5335 | 0.5362 | 0.5340 | 0.5866 | 0.5733 |
| *TCRIS* | 1 | 0.875 | 0.875 | 0.875 | 0.875 |
| *RCRIS* | 0.5335 | 0.4692 | 0.4672 | 0.5132 | 0.5016 |
| **Index** | **Solution 6** | **Solution 7** | **Solution 8** | **Solution 9** | **Solution 10** |
| *ECRIS* | 4.0*10$^3$ | 3.9*10$^3$ | 4.0*10$^3$ | 4.0*10$^3$ | 4.1*10$^3$ |
| *XCRIS* | 0.5457 | 0.5960 | 0.6049 | 0.4944 | 0..4911 |
| *TCRIS* | 0.7778 | 0.6667 | 0.7778 | 0.7778 | 0.6667 |
| *RCRIS* | 0.4244 | 0.3973 | 0.4705 | 0.3845 | 0.3274 |
| **Index** | **Solution 11** | **Solution 12** | **Solution 13** | | |
| *ECRIS* | 3.9*10$^3$ | 2.9*10$^3$ | 2.8*10$^3$ | | |
| *XCRIS* | 0.5690 | 0.5582 | 0.5433 | | |
| *TCRIS* | 0.6667 | 0.4167 | 0.4167 | | |
| *RCRIS* | 0.3793 | 0.2326 | 0.2264 | | |

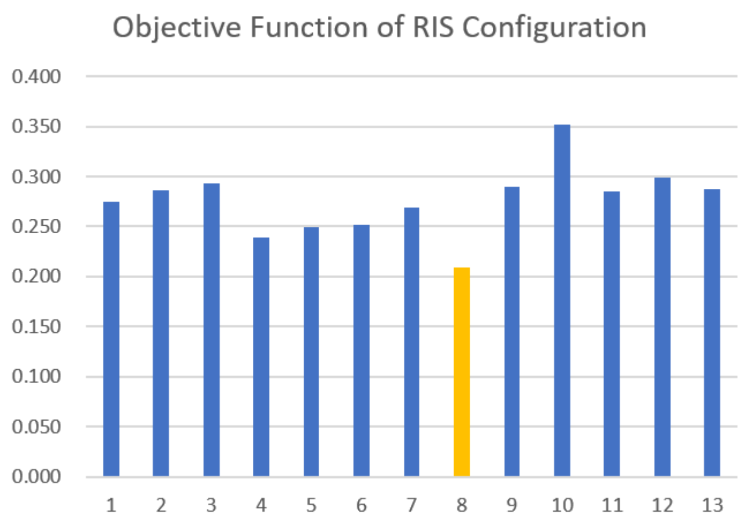



**Figure 6.24. The Result of RIS Configuration Design Objective Function**

According to the changing tendency of RIS feasible design performance level, Figure 6.24, Scheme 5 has the lowest objective function value, and its economic cost and diagnosability reach a relative balance, that is, Scheme 5 is the satisfied RIS configuration solution. In the current process route, the satisfied quality detection relies on four RIMs and focuses on the downstream area.

### 6.4.3 Application of RMS Configuration Design

The replacement of automotive product designs is accelerating at a faster rate leading to an increasing degree of disparity of the cars. Hence, the design of the engine is also changing accordingly. Currently, the common engine structures include in-line four-cylinder engine (L4), V-type six-cylinder engine (V6) or V-type eight-cylinder engine (V8). Under the circumstances mentioned above, different cars choose different types of engines based on parameters such as displacement or noise reduction. For example, the Audi S3 uses the L4 engine, the Audi A6 uses the V6 engine, and the Audi A8 uses the V-type eight-cylinder engine. The cylinder block of the L4 and V8 engines presented in Figure 6.25. In this context, the enterprises try to enhance their manufacturing system's adaptability to accommodate dynamic market demand. With the premise of maintaining low cost and high quality, the enterprises produce more diverse parts to meet the requirements of different automotive assembly and improve the competitiveness of the enterprise. Therefore, in the automotive industry, the RMS has unlimited development and application space, and the RMS is an indispensable new manufacturing force for the future emerging enterprises. Therefore, the proposed method, Section 6.4, for exploring the RMS reconfiguration strategy is demonstrated via manufacturing the engine cylinder block.

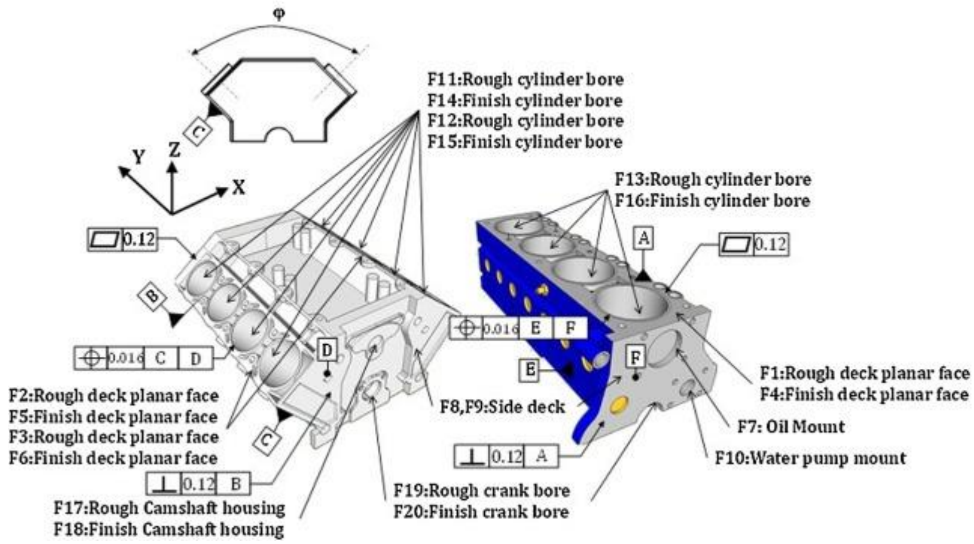



**Figure 6.25. The Example of the L4 (right) and V8 (left) Engine Block (Abbas, et al., 2016)**

The machining characteristics of the engine cylinder block include multiple machining surfaces and holes, and the required machining accuracy is also different. Therefore, the premise of parts processing is the reasonable arrangement and division of the process route. In this example, we explore the RMS reconfiguration strategy in two scenarios. First scenario is the transitions between different parts families lead to the RMS reconfiguration. The second scenario is the transitions between different parts in one part family lead to RMS reconfiguration. According to the structure of the cylinder block, two families of parts to be machined are extracted, which are respectively an L-type engine block and a V-type engine block. The linear engine cylinder block family includes one component, the L4 engine block. The V-type engine block family includes two components, the V6 engine block and the V8 engine block. Therefore, the first design requirement is reconfiguring RMS to match from the L4 engine block to the V6 engine block. The second design requirement is reconfiguring RMS to match from the V6 engine block to the V8 engine block.

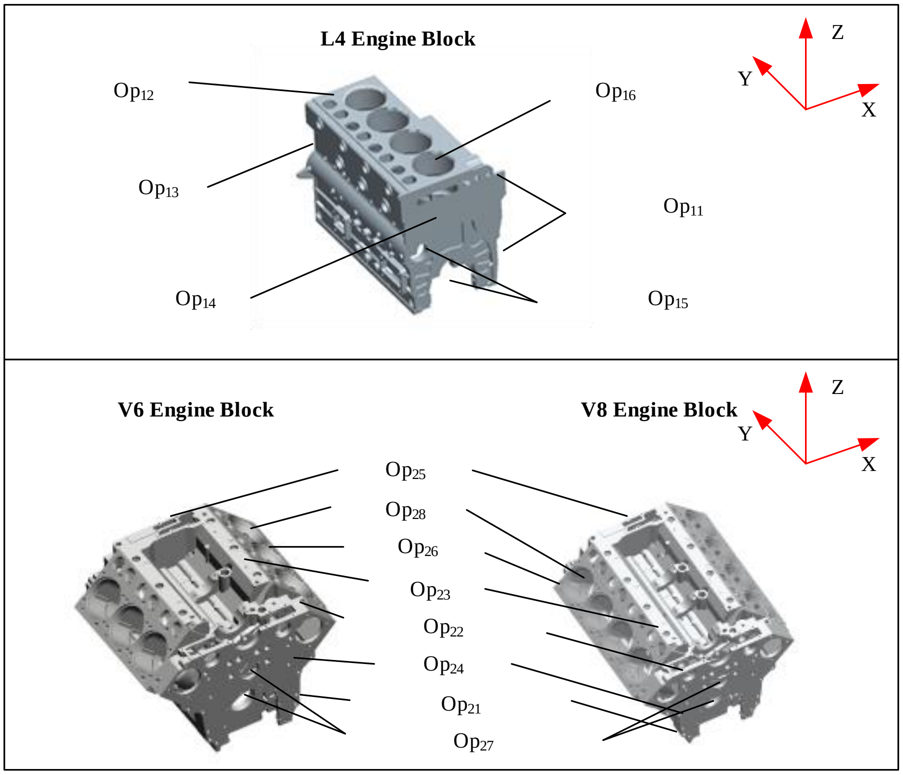



**Figure 6.26. The Example of Three Types of the Cylinder Block**

Before the detailed design of the reconfiguration configuration, the processing routes of the above three engine blocks ought to be analyzed. Due to the large number of machining features of the cylinder block, we consider the key operations in text example. The L4, V6, and V8 engine blocks considered in this case were sourced from a company as shown in Figure 6.26, while the key operating information is shown in Table 6.20 and Table 6.21. During the reconstruction process, the process of the L4 engine block is Op11- Op12 - Op13 - Op14 - Op15 - Op16; the process route of the V6 engine block is Op21 - Op22 - Op23 - Op24 - Op25 - Op26 - Op27 - Op28; to reduce the fixture error caused by the fixture change, the V8 engine block's process path change is Op21 - Op25 - Op22 - Op23 - Op24 - Op27 - Op26 - Op28.

**Table 6.20. Key Operation for L4 Engine Cylinder Production**

| Num | Manufacturing operations | Manufacturing Features | Reference Surface |
|---|---|---|---|
| 1 | $Op_{11}$ | XYZ | Undersurface and two locating pin holes |
| 2 | $Op_{12}$ | XYZ | Side datum, position shoulder and two pin holes |
| 3 | $Op_{13}$ | XYZ | Side datum, position shoulder and two pin holes |
| 4 | $Op_{14}$ | XYZ | Side datum, position shoulder and two pin holes |
| 5 | $Op_{15}$ | YZB | Side datum, position shoulder and two pin holes |
| 6 | $Op_{16}$ | YZC | Side datum, position shoulder and two pin holes |

**Table 6.21. Key Operation for V6 and V8 Engine Cylinder Production**

| Num | Manufacturing operations | Manufacturing Features | Reference Surface |
|---|---|---|---|
| 1 | $Op_{21}$ | XYZ | Undersurface and two locating pin holes |
| 2 | $Op_{22}$ | XYZ | Side datum, position shoulder and two pin holes |
| 3 | $Op_{23}$ | XYZ | Side datum, position shoulder and two pin holes |
| 4 | $Op_{24}$ | XYZ | Side datum, position shoulder and two pin holes |
| 5 | $Op_{25}$ | XYZ | Side datum, position shoulder and two pin holes |
| 6 | $Op_{26}$ | XYZB | Side datum, position shoulder and two pin holes |
| 7 | $Op_{27}$ | YZB | Side datum, position shoulder and two pin holes |
| 8 | $Op_{28}$ | XYZBC | Side datum, position shoulder and two pin holes |

The RMS initial configuration is designed to meet the requirements of manufacturing the L4 engine block. In order to simply and directly represent the configuration design, the system or subsystem configurations are represented using a block diagram, and the specific configuration of the device is represented by a configuration tree. The initial configuration of the RMS in this text example is shown in Figure 6.27. This configuration has a total of 9 work stations, of which 6 are RMTs and three are RIMs. Each RMT configuration is shown in the corresponding configuration tree. The first production partition contains RMT 1, that is, RIM 1 detects the state of RMT 1, and RIM 1 includes four sensors. The second production partition contains four machine tools: RMT 2, RMT 3, RMT 4 and RMT 5, that is, RIM 2 is to inspect the states of these four machine tools and RIM 2 has eight sensors. The final production partition contains RMT 6, which is the RIM 3 detects the state of RMT 6, and the number of sensors is four.

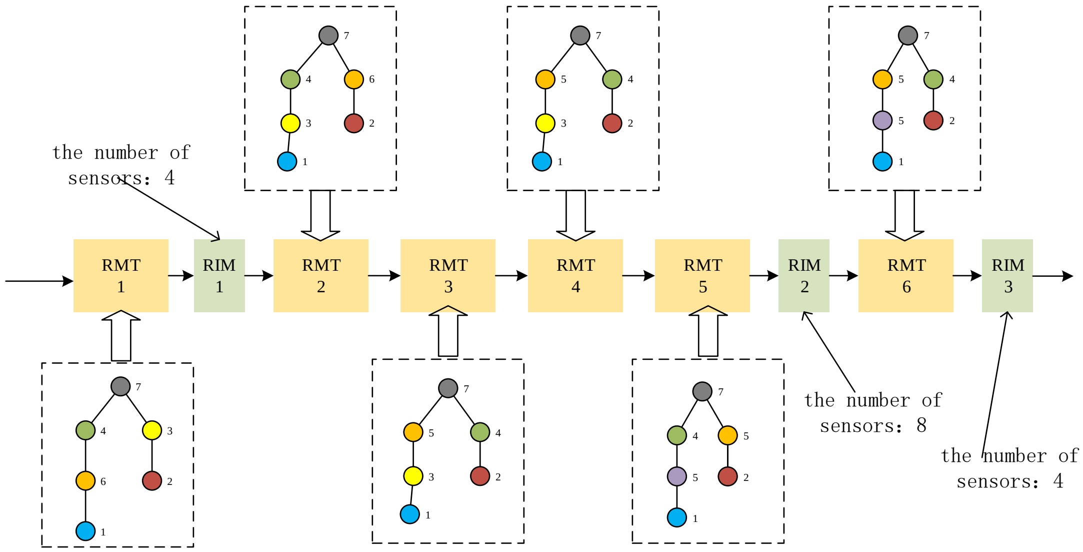



**Figure 6.27. The RMS Initial Configuration in Text Example**

In addition, in order to consider the company's personality and preferences, the company's manufacturing needs were investigated and the required parameter data were extracted, including module fixing and assembly costs and the number of modules of the machine tool (one machining operation per machine tool). Sensor reliability (average 0.9), sensor cost (the average is \$146), detector installation cost (the average is \$1460), quality inspection time (up to 3 units of work), and company's expected investment cost (less is better), the number of work units expected by the company (no more than 12), etc.

The reconfiguration process of this case consists of two stages, which are respectively from the L4 engine cylinder block to the V6 engine block and from the V6 engine block to the V8 engine block. In order to simplify the description, the following two phases of reconfiguration are represented by Phase A and Phase B, respectively. The requirement in the Phase A is the conversion between different part families led to the reconfiguration of the system. The designers need to re-design and reconfigure the production process and detection process. For the problem of multi-granularity interactions existing at this stage, the cooperative model in Figure 6.11 is used to explore the solutions. The satisfied solution for Phase A is addressed as shown in Figure 6.28.

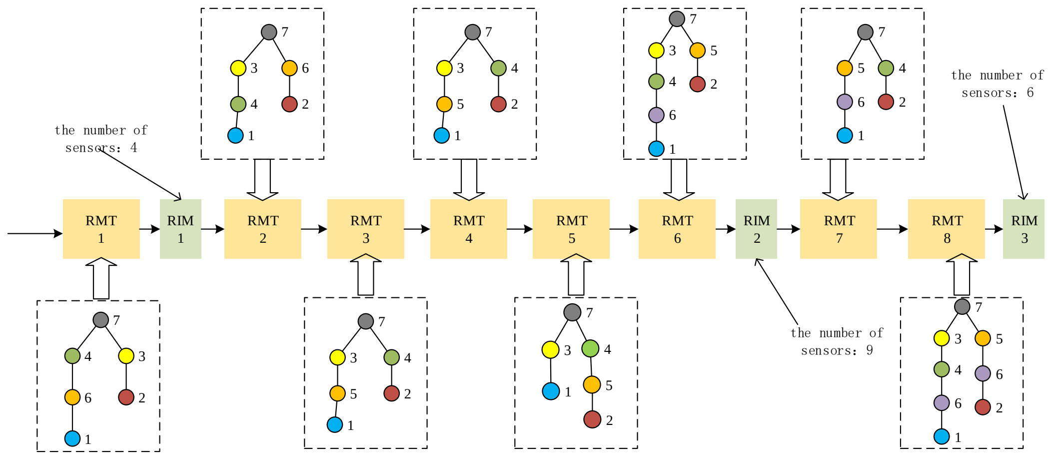



**Figure 6.28. The Solution of Phase A with the Cooperative Model**

The design of Phase B belongs to the conversion of different parts between the same part families, leading to the reconfiguration of the system. Normally, there are many similar processes with the parts in the part family, so designers are more focused on optimizing the detection process. Since the inspection process may change as the production process changes, the production process is designed first, and then the inspection process is formed for a specific production process. Therefore, the leader-follower model is used to solve this stage, and the leader is the RMT configuration design. The satisfied solution for Phase B presented in Figure 6.29.

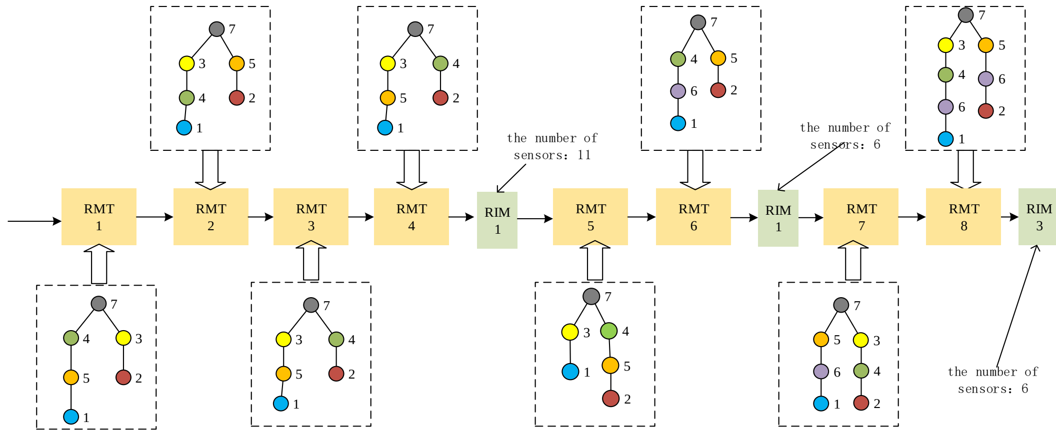



**Figure 6.29. The Solution of Phase B with the Cooperative Model**

The reconfiguration process of a RMS becomes more complicated as the number of workstations increases. For example, there are 71 feasible design for the reconfiguration of detection process in RMS with 12 workstations. The configuration design method based on cDSP construction and game theory can effectively solve the space exploration process. According to the reconfiguration strategy, the results obtained by the proposed method can make the good use of the original resources. For example, the process path of the cylinder block of the L4 engine has the same processing characteristics as the first four steps of the process line of the cylinder of the V6 engine. The corresponding configuration in the design is also the same, so as to effectively avoid unnecessary reconfiguration. At the same time, different interaction relationships can be used to describe the priorities and priorities among designers. For example, the reconfiguration of Phase A corresponds to different part families. Therefore, both the production process and the detection process need to be reconfigured, so that the cooperation model is applied. The solution also maximizes the balance between reconfigurability and diagnosability. Phase B corresponds to different parts and has many similar processes. Therefore, the reconfiguration of the detection process is more affected by the production process, so the leader-follower model is applied. The resulting design solution improves the diagnosability of the specific production process during the processing of the part family.

## 6.5 Synopsis of Chapter 6

In this chapter, Empirical Structural and Performance Validity of the Research Question 3 "*What is the reconfiguration strategy for reestablishing connection among elements in the system in realization of networked engineering systems to remain competitive on the market?*" is addressed. The answer is the strategy for reconfiguration of machine tool, Section 6.1, inspection system, Section 6.2, and manufacturing system, Section 6.3. The empirical structural validity of the method, Quadrant 2 of the Validation Square, is presented in Sections 6.1 – 6.3. The empirical performance validity of the method, Quadrant 3 of the Validation Square, is presented in Section 6.4.

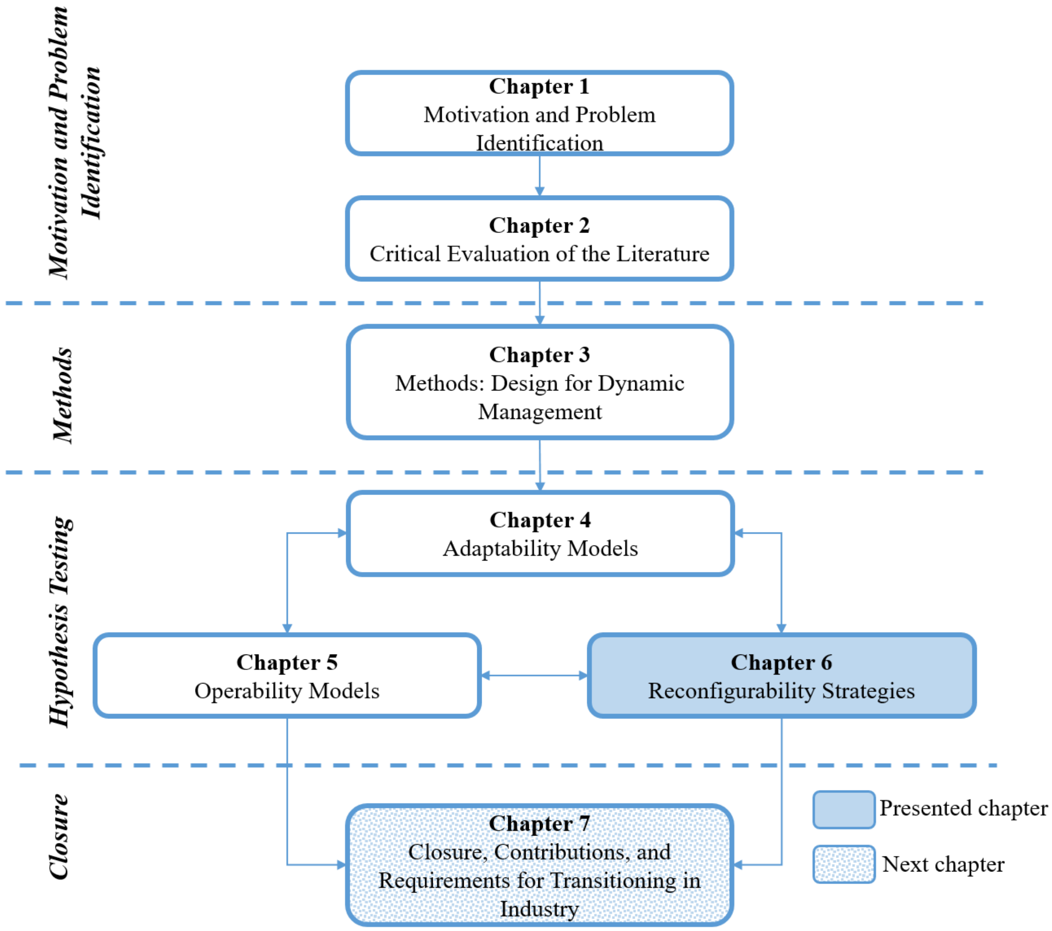



**Figure 6.30. Organization of the Dissertation – Presented and Next Chapter**

In Chapter 7, see Figure 6.30, a summary of dissertation is presented where the research questions and validate the hypothesis are presented in Section 7.2. Further, contributions and limitations of the proposed methods regarding adaptability, operability, and reconfigurability are presented in Section 7.3. Lastly, a way forward, requirements for the computational framework, Design for Dynamic Management, to transit to industry are established and presented in Section 7.4.

# CHAPTER 7

# CLOSURE

The principal goal in this dissertation is to create a new knowledge, make a transformative influence in the design of networked engineering systems adaptable to ambitious market demands, and to accommodate the Industry 4.0 design principles based on the philosophy that design is fundamentally a decision making process. The primary motivation in this dissertation is to establish a computational framework that is suitable for the design of networked engineering systems adaptable to ambitious market demands, therefore, frame the problem, identify research gaps in this dissertation, and define research questions that will be further addressed in future work.

In this chapter, a summary of the dissertation is presented in Section 7.1. The research questions and research hypothesis introduced in Chapter 1 are revised and critically evaluated with a special emphasis on the validity of the research hypothesis in Section 7.2. Further, expected contributions and identified limitations are presented in Section 7.3. Lastly, the motivation for a way forward, research gaps and research questions that will be addressed in future work are proposed in Section 7.4., where the goal is to identify requirements for Architecting Networked Engineering Systems to transit in industry. In summary, in this chapter, the connection between research questions and hypothesis, contributions and limitations, and future work is established, Table 7.1.

**Table 7.1. Connection between Research Questions, Contributions, Limitations, and Future Work**

| Research Questions | Contributions | Limitations | Future Work |
|---|---|---|---|
| What is the computational framework in the design method that facilitates adaptable design in the realization of networked engineering systems? **Section 7.2.1** | ▪ Identifying drivers and relations in concurrent design,<br>▪ Build in flexibility in selection/determination of design parameters,<br>▪ Managing the high-complexity mathematical problem,<br>▪ Creating decision network structure as a decision support,<br>▪ Integration of process- and product-related decision models.<br>**Section 7.3.1** | ▪ Capture the knowledge in design of NES,<br>▪ Multidisciplinary knowledge exchange between different domains,<br>▪ Interfacing domain ontologies, converting different analogies between different domains.<br>**Section 7.3.1** | Knowledge-Based Decision-Based Design Ontology **Section 7.4.1** |
| What is the computational framework in the design method that facilitates dynamic change in the requirements in realization of functional networked engineering systems? **Section 7.2.2** | ▪ Framing operability/disturbance space without domain knowledge,<br>▪ Operability analysis of any engineering systems,<br>▪ Managing dynamic performance of the system.<br>**Section 7.3.2** | ▪ Decision-based design templates for integrating consumer and producer preferences,<br>▪ Managing dynamic performance of any system,<br>▪ Decision-based design decision network for managing dynamic performance.<br>**Section 7.3.2** | Decision-Based Design Platform **Section 7.4.2** |
| What is the reconfiguration strategy for reestablishing connection among elements in the system in realization of networked engineering systems to remain competitive on the market? **Section 7.2.3** | ▪ Reconfiguration strategy of manufacturing tool,<br>▪ Reconfiguration strategy of inspection system,<br>▪ Reconfiguration of manufacturing system.<br>**Section 7.3.3** | ▪ Multiple configurations of elements from different systems,<br>▪ Reach sustainability by integrating cyber-physical-social systems in design,<br>▪ Cyber-social design decision network sensitive to dynamic changes of consumer`s and producer`s preferences in design.<br>**Section 7.3.3** | Integration of Cyber-Physical-Social Systems in the Platform **Section 7.4.3** |

## 7.1 A Summary of the Dissertation

The need for low-cost products in the global marketplace has led to large-scale globalization and automation of manufacturing processes. However, the dynamic changes in the market due to the wide variations in customers' preferences require these enterprises to be capable of globally adjusting the manufacturing processes to meet these demands in a timely manner. Further, global competition requires enterprises not only to provide cost-effective manufacturing processes but also to improve the quality of product and shorten time to market. Digitization of networked manufacturing systems (NMSs) is one technology that is increasingly being adopted to respond to changes in the marketplace. Hence, there is an emerging need for methods to design systems adaptable to dynamic changes in the market. Therefore, the decision-based design computational framework, Design for Dynamic Management, is proposed as a means of achieving the flexible design, performing end-to-end analysis at design time, and assessing connectivity requirements among system components and their impact on the overall performance of the system. This is achieved by (1) adaptable concurrent design, flexibility in selection of design parameters and concurrent design of the mechanical and control systems, without a domain knowledge, (2) operability analysis, determine the functionality of the system in the presence of change, and (3) reconfiguration strategy, reestablish connectivity and allow multiple reconfigurations among multiple elements in the system.

In this dissertation, it is shown that integration of adaptability, operability, and reconfigurability in the design of systems of a high order is necessary for further digitalization of networked engineering systems (smart manufacturing). Furthermore, current approaches are neither agile nor rapidly configurable and do not have built-in flexibility in selection and determination of values of design parameters, such as tools and/or sensor, and tolerances for errors that are introduced, accumulated and propagated in the process.

In addition to engineering systems, the framework, Figure 7.1, and models developed in this dissertation can be generalized and applied to product development and design service systems, etc. This computational framework is named Architecting Networked Engineering Systems.

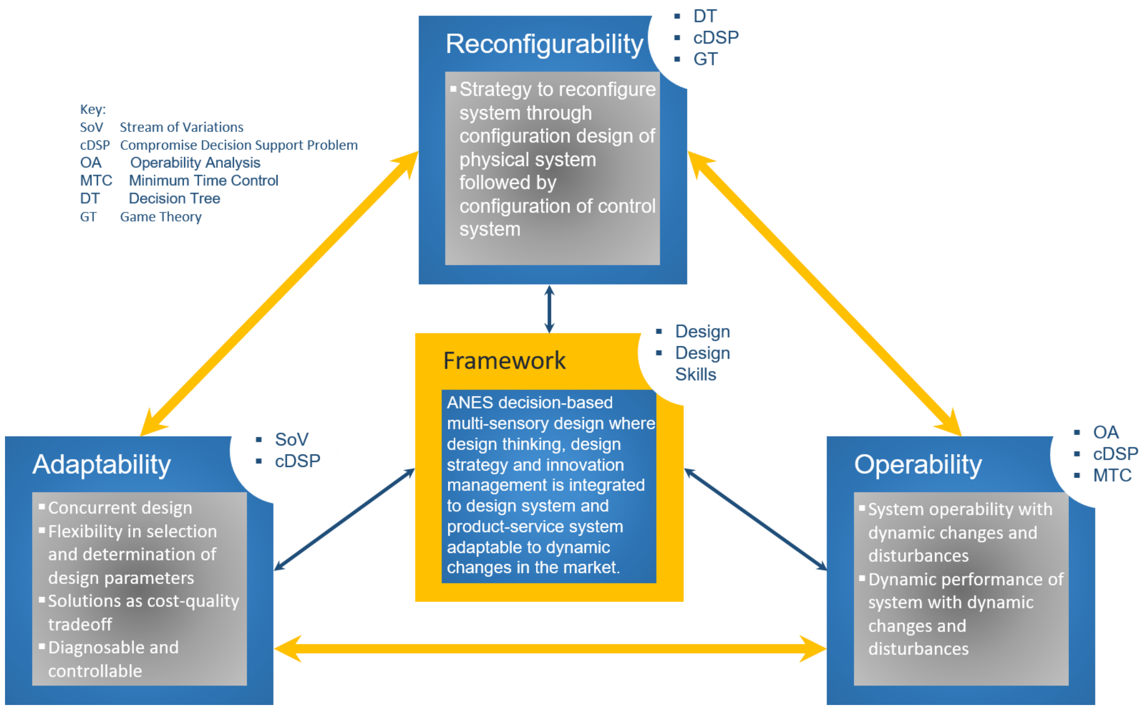



**Figure 7.1. Architecting Networked Engineering System (ANES) Framework**

## 7.1.1 Adaptable Concurrent Realization of Networked Engineering Systems (ACRONES)

Networked engineering systems such as multistage manufacturing processes (MMPs) are complex processes consisting of multiple manufacturing stations and operations and are commonly encountered in applications such as automotive machining, assembly of electronic products, and semiconductor lithography processes (Shi and Zhou, 2009). Ensuring quality of the produced goods in these MMPs requires the capability to detect defects, identify their likely causes and then adjust control parameters to eliminate or reduce these defects. In the past, given an implementation of MMP, state-space representation of the MMP was first derived and this mathematical representation was then used to analyze the root cause of failures (Ding et al., 2002). This representation was also used to determine whether the implementation was controllable, i.e., if the cause of the defect could be eliminated through the proper adjustment of control parameters. While this approach is suited for analyzing the properties of MMP, it is not useful for selecting sensing and control components and their respective placements in the MMP. Further, the overall cost and performance of the MMP are dictated by this choice and are hard to ascertain at design time. Next generation manufacturing processes have to be adaptable, i.e., able to handle many different product types, robust to fixturing and other forms of errors that can degrade product quality, and offer cost-effective implementation of the entire process.

The author`s research focus is to identify, understand the principles and propose a theory that is foundational to a method for the concurrent design of an n-stage manufacturing process that has flexibility, adaptability, and robust NMSs built into it when the mechanical and control systems are designed concurrently. Concurrent design and computational complexity are managed by instantiating the compromise Decision Support Problem (cDSP) construct (Smith et al., 2014 and 2015). In this dissertation, a systematic method for the concurrent design and analysis of multistage manufacturing processes is proposed. The method is used to exploit the flexibility in selection and determination of the values of process/systems variables at design time to simultaneously address requirements such as controllability and diagnosability and lower the overall cost during the execution of MMP cDSPs while ensuring that system constraints are satisfied, see Quadrant 1 in Figure 7.1.

The method is based on the compromise Decision Support Problem (cDSP) construct (Mistree, et al., 1992) for MMP, where MMP is described by a Stream of Variation (SoV) model (Ding et al., 2000), Figure 1.7. The proposed method is illustrated using an example of an automotive panel stamping process. The results are presented in several publications (Milisavljevic, 2015; Milisavljevic-Syed, et al., 2018; Milisavljevic, et al., 2017).

### 7.1.2 Operability in Dynamic Management in the Realization of Networked Engineering Systems

One of the challenges of networked engineering systems is big data analysis in real time. The author of this dissertation advocate that this challenge can be addressed by analyzing the real-time functioning of the system in the presence of fluctuations in market demand. Analyzing the system functionality of NMSs is possible through operability analysis. Operability analysis presents the bound between the design of the process and control of the process (Georgakis, et al., 2003). The author`s research focus is to analyze the dynamic and steady-state performance of the manufacturing system as the system requirements change. Operability analysis is accomplished in two stages (1) steady-state operability analysis, and (2) dynamic operability analysis.

***System Operability at Steady-State.*** The steady-state operability is used to analyze how different requirements, driven by customer needs, are changing system functionality. System functionality is analyzed using Steady-State Operability Model

(SSOM) that is based on operability analysis and compromise Decision Support Problem (cDSP) construct. The cDSP construct is used to manage the structure and information of decision-making, Quadrant 2 in Figure 7.1.

The solution scheme of the steady-state operability model is presented in Figure 5.4. The proposed method is illustrated using an example of an automotive panel stamping process. The results are presented in publication Milisavljevic-Syed (Milisavljevic-Syed, et al., 2018).

***Dynamic System Operability.*** The dynamic operability is used to analyze how different requirements are changing system functionality over time. Dynamic performance of a system is analyzed by Dynamic Operability Model (DOM) that is based on operability analysis and minimum-time control, see Quadrant 2 in Figure 7.1.

The solution scheme of dynamic operability model is presented in Figure 5.8. The proposed method is illustrated using an example of continuous stirred tank reactors.

### 7.1.3 Realization of Dynamic Management in Reconfigurable Manufacturing System

Connectivity among elements in the system is required for a new generation of engineering systems. However, this is not always possible and there is a need for establishing a connection through the reconfiguration of the engineering system. Reconfigurable Manufacturing System (RMS) can provide customized manufacturing process to meet the changes in operational requirements or machine status. The effective realization of RMS is supported by the Design for Dynamic Management that is detecting the process errors and exploring the reconfiguration strategy, Quadrant 3 in Figure 7.1.

The reconfiguration is accomplished in two stages (or two parts) (1) reconfiguration of machine tools (RMT), and (2) reconfiguration of the inspection system (RIS).

A Reconfigurable Machine Tool (RMT) is repeatedly configured in order to respond to a wide range of requirements, such as the change in function or capacity. Module selection and the assembly relationships among modules in the end-assembly of the machine tool are main to any method for configuration design of reconfigurable machine tools. Typically, module models reside in different libraries and their descriptions vary. In this research, a tree-based method is proposed to tie information in different libraries (Wang, et al., 2017). The method includes (1) defining a common model for reconfigurable machine tool configuration using a tree structure; (2) identifying concepts that combine the desired function and capability; and (3) determining those concepts while minimizing cost and maximizing flexibility.

Typically, research in reconfiguration revolves around production while ignoring the inspection. In the RMS, Reconfigurable Inspection System (RIS) is defined to achieve the data-oriented detection of the product quality with the minimum but sufficient inspection machines. Thus, a key feature-based method is proposed for RIS configuration design to determine the satisfied RIS design (number of inspection stations, number of sensors and their position) that detects the different process, thereby meets the inspectional requirement for each phase of RMS lifecycle. First, the key features of RIS (i.e., Modularity, Integratability, Customization, Scalability, Convertibility, and Diagnosability) are identified based on the detection mechanism of the RMS. Second, the model-based specific procedure to explore the RIS configuration design is introduced to ensure the RIS satisfies the multiple constraints (i.e., inspectional functionality and capability) and goals (i.e., cost and diagnosability). The results are presented in publications (Milisavljevic-Syed, et al., 2018; Shang, et al., 2018).

## 7.2 Answering the Research Questions and Validating the Hypotheses

The principal goal in this dissertation is to is to create a new knowledge, make a transformative influence in the design of networked engineering systems adaptable to ambitious market demands, and to accommodate the Industry 4.0 design principles based on the philosophy that design is fundamentally a decision making process. The primary motivation is to establish a computational framework that is suitable for the design of low cost and high-quality networked engineering systems adaptable to ambitious market demands in the context of Industry 4.0. The concept of computation framework is exploited in the context of the primary research question as presented in Chapter 1, Section 1.4.

***Primary Research Question.*** *In the context of Industry 4.0 what is the computational framework that facilitates the decision-based design of networked engineering systems adaptable to ambitious market demands as a support to further digitization?*

***Hypothesis for the Primary Research Question.*** *The author hypothesizes, that by applying computational framework, we can obtain knowledge of the networked engineering system, and by incorporating the knowledge to design system adaptable to ambitious market demands, further digitization of NES can be ensured.*

The primary research question, Chapter 1, Section 1.4.2, unifies secondary research questions. Research Question 1 addresses adaptable concurrent design of networked engineering system. Research Question 2 addresses operability analysis of networked engineering systems. Research Question 3 addresses reconfiguration strategy of networked engineering systems. The knowledge we obtain by answering the Research Question 1 is further used to answer the Research Questions 2, and knowledge we obtain by answering the Research Question 2 is further used to answer the Research Questions 3.

***Research Question 1.*** *What is the computational framework in the design method that facilitates adaptable design in the realization of networked engineering systems?*

***Research Question 2.*** *What is the computational framework in the design method that facilitates dynamic change in the requirements in the realization of functional networked engineering systems?*

***Research Question 3.*** *What is the reconfiguration strategy for reestablishing connection among elements in the system in the realization of networked engineering systems to remain competitive on the market?*

Hypotheses are identified to answer secondary research questions and support the principal goal in this dissertation. Further, the end result is a new knowledge, a computational framework suitable for the design of low cost and high-quality networked engineering systems adaptable to ambitious market demands, and identifying research gaps for future research. Validation of the hypotheses is discussed in details in each chapter according to validation roadmap presented in Chapter 1, Section 1.5. Further, validation of hypotheses is revisited and summarized in Tables 7.2 – 7.4 in Sections 7.2.1 – 7.2.3.

### 7.2.1 Hypothesis 1. Adaptable Concurrent Design of Networked Engineering Systems

In this section, Hypothesis 1 is discussed in order to answer the Research Question 1. Hypothesis 1 is introduced in Chapter 1 and further addressed in Chapter 4 as presented in Table 7.2.

***Hypothesis for Research Question 1.*** *Design of mechanical and control system concurrently while accounting for different types of uncertainty and extensive (robust) solution space exploration facilitates the adaptable design of networked engineering system.*

***Theoretical Structural Validation.*** There is a need for integrating flexibility in the selection of design parameters and the concurrent design of the mechanical and control systems by introducing adaptable concurrent design. Hence, Hypothesis 1 is the important link in the computational framework, Design for Dynamic Management, due to dynamic changes in the design of networked engineering systems. A motivation for the decision-based design of networked engineering system, Section 1.1, and background of the concurrent design of a mechanical and a control system, Section 1.2.1., are introduced. Existing design approaches are presented in Section 2.1. A problem of decision-based design of networked engineering system, Section 3.1, and a general cDSP formulation are presented in Section 3.2. Mathematical background of decision-based design, Section 3.3, a particular mathematical model for the adaptable concurrent design of networked engineering systems is presented in Section 3.3.1. Further, the overall computational framework, Design for Dynamic Management, is discussed in Section 3.4.,

Figure 3.8., and a method, Adaptable Concurrent Realization of Networked Engineering Systems, is presented in Section 4.1.

**Table 7.2. Summary of Validation of Hypothesis 1**

| Hypothesis | Validation | Details |
|---|---|---|
| **Hypothesis 1** Design of mechanical and control system concurrently while accounting for different types of uncertainty and extensive (robust) solution space exploration facilitates flexible design of networked engineering system. | Theoretical Structural Validation | |
| | Motivation for adaptable concurrent design of NES | §1.1.2 |
| | Introduction to concurrent design of NES | §1.2.1 |
| | Mathematical background of adaptable concurrent design model | §3.3.1 |
| | Literature review | §2.1 |
| | Empirical Structural Validation | |
| | Test example of panel assembling process | §3.1.3, Figure 3.2 |
| | Designing networked engineering systems concurrently | §4.1.1, Figure 1.7 |
| | Managing problem structure | §4.1.2, Figure 4.3 |
| | Solution space exploration | §4.1.3 |
| | Robust solution space exploration | §4.1.4, Figure 4.5 |
| | Empirical Performance Validation | |
| | Adaptable Concurrent Realization of Networked Engineering Systems (ACRONES) | §4.1, Figure 4.2 |
| | The comprehensive mathematical model | §4.2 |
| | The cost-quality relationship analysis | §4.3, Figure 4.11 – 4.14 |

***Empirical Structural Validation.*** Adaptable Concurrent Realization of Networked Engineering Systems (ACRONES) is a comprehensive model that consist of (1) model for concurrent design of NES, (2) managing problem structure by integrating process decision models (diagnosability, controllability, and cost-effectiveness) with product quality models (performance measurement) in comprehensive adaptability model, (3) solution space exploration, and (4) robust solution space exploration. Concurrent design of NES for identifying flexible design parameters, establishing their connectivity, and representing the process with a comprehensive state space model is presented in Section 4.2.1. Managing problem structure for determining interconnections between networked engineering system modules and the mathematical representation of the complete system is presented Section 4.2.2. Solution space exploration for exploring the solution space for appropriate solutions is presented in Section 4.2.3. Robust solution space exploration for identifying and managing different types of uncertainty, exploring solution space, and identifying robust solutions to the design problem is presented in Section 4.2.4. Models for adaptable concurrent design include drivers from both the mechanical and control system, unifies simulation parameters, and represent the appropriate example for validating the Hypothesis 1.

***Empirical Performance Validation.*** Adaptable Concurrent Realization of Networked Engineering Systems (ACRONES) is a design method, a part of the computational framework, Design for Dynamic Management. Empirical performance validity of the ACRONES is performed in four steps (1) concurrent design of NES, (2) managing problem structure, (3) solution space exploration and locating solutions as a cost-quality tradeoff, and (4) robust solution space exploration and locating robust solutions as a cost-quality tradeoff. ACRONES is presented in Section 4.2. Empirical performance validation of the ACRONES is presented in Section 4.4.

### 7.2.2 Hypothesis 2. Operability Analysis of Networked Engineering Systems

In this section, Hypothesis 2 is discussed in order to answer Research Question 2. Hypothesis 2 is introduced in Chapters 1 and further addressed in Chapter 5, as presented in Table 7.4. Hypothesis 1 is a support to operability analysis presented in Hypothesis 2.

***Hypothesis for Research Question 2.*** *Determining input ranges (operability and disturbance spaces) that give desired solution range of functional system design at steady-state and dynamic state that will allow a system to adjust and stabilize in presence of change.*

***Theoretical Structural Validity.*** There is a need for operability analysis that is used to determine the functionality of the system undergoing dynamic changes. Hence, the Hypothesis 2 is the important link in the computational framework, Design for Dynamic Management, due to dynamic changes in the design of networked engineering systems. The motivation for decision-based design of networked engineering system is presented in Section 1.1. Existing design approaches are presented in Section 2.2. A problem of decision-based design of networked engineering system, Section 3.1, and a general cDSP formulation are presented in Section 3.2. Mathematical background of decision-based design, Section 3.3, particularly mathematical model for operability analysis in design of networked engineering systems is presented in Section 3.3.2. Further, the overall computational framework, Design for Dynamic Management, is discussed in Section 3.4., Figure 3.8, and a method, Operability in Dynamic Management, is presented in Section 5.1.

**Table 7.3. Summary of Validation of Hypothesis 2**

| Hypothesis | Validation | Details |
|---|---|---|
| **Hypothesis 2** Determining input ranges (operability and disturbance spaces) that give desired solution range of functional system design at steady-state and dynamic state that will allow a system to adjust and stabilize in presence of change. | <u>Theoretical Structural Validation</u> | |
| | Motivation for operability analysis in design of NES | §1.1.2 |
| | Mathematical background of operability analysis model | §3.3.2 |
| | Literature review | §2.2 |
| | <u>Empirical Structural Validation</u> | |
| | Test example of continuous stirred tank reactors | §3.1.3, Figure 3.3 |
| | Steady-state operability model | §5.2, Figure 5.4 |
| | Dynamic operability model | §5.3, Figure 5.8 |
| | <u>Empirical Performance Validation</u> | |
| | Operability analysis model | §5.1 |
| | Steady-state operability model | §5.4.1, Appendix B |
| | Dynamic operability model | §5.4.2, Appendix C |

***Empirical Structural Validity.*** Operability analysis model is a comprehensive model that consists of (1) steady-state operability model (SSOM), Section 5.2, and (2) dynamic operability model (DOM), Section 5.3. The steady-state operability model (SSOM) analyses the operability spaces obtained from ACRONES and disturbance spaces formed by customer needs in order to identify possible solutions of the functional system. The dynamic operability model (DOM) examines dynamic performance of the system undergoing dynamic changes. Operability models are foundation for analyzing the functionality of the system undergoing dynamic changes, therefore, represent the appropriate example for validating Hypothesis 2.

***Empirical Performance Validity.*** Operability analysis is a design method, a part of the computational framework, Design for Dynamic Management. Empirical performance validity of the operability analysis is performed in three steps (1) obtaining information from ACRONES to frame operability spaces and information form customer to frame disturbance spaces, (2) steady-state operability analysis of the system, and (3) dynamic performance of the system and locating operable(functional) solutions. Operability analysis is presented in Section 5.1. Empirical performance validation of the operability analysis is presented in Section 5.4.

### 7.2.3 Hypothesis 3. Reconfiguration Strategy of Networked Engineering Systems

In this section, Hypothesis 3 is discussed in order to answer Research Question 3. Hypothesis 3 is introduced in Chapter 1 and further addressed in Chapter 6, as presented in Table 7.3.

***Hypothesis for Research Question 3.*** *Machine tool reconfiguration followed by inspection system reconfiguration will allow reconfiguration of the manufacturing system and re-establishing connection among elements in the system.*

***Theoretical Structural Validation.*** There is a need for reconfiguration strategies that are used to allow multiple configurations of elements in the system if required. Hence, Hypothesis 3 is the important link in computational framework, Design for Dynamic Management, due to dynamic changes in the design of networked engineering systems. The motivation for the decision-based design of networked engineering system is presented in Section 1.1. Existing reconfiguration strategies are presented in Section 2.3. A problem of decision-based design of networked engineering system, Section 3.1, and a general cDSP formulation are presented in Section 3.2. Mathematical background of decision-based design, Section 3.3, a particularly mathematical model for reconfiguration strategy in design of networked engineering systems is presented in Section 3.3.3. Further, the overall computational framework, Design for Dynamic Management, is discussed in Section 3.4., Figure 3.8, and a method, Reconfigurable Manufacturing System, is presented in Section 6.3.

***Empirical Structural Validation.*** Reconfigurable Manufacturing System (RMS) is a comprehensive model that consists of (1) Reconfigurable Machine Tool (RMT), Section 6.2, and (2) Reconfigurable Inspection System (RIS), Section 6.3. The Reconfigurable Machine Tool (RMT) is a reconfiguration strategy for a machine tool in the manufacturing system. The Reconfigurable Inspection System (RIS) is a reconfiguration strategy of inspection tool in the manufacturing system. Reconfiguration strategies are the foundation for reconfiguration of manufacturing system which allows multiple simultaneous configurations of elements in the system in same time, therefore, represent the appropriate example for validating Hypothesis 3.

**Table 7.4. Summary of Validation of Hypothesis 3**

| Hypothesis | Validation | Details |
|---|---|---|
| **Hypothesis 3** Machine tool reconfiguration followed by inspection system reconfiguration will allow reconfiguration of manufacturing system and reestablishing connection among elements in the system. | <u>Theoretical Structural Validation</u> | |
| | Motivation for reconfiguration strategy in design of NES | §1.1.2 |
| | Mathematical background of reconfiguration strategy | §3.3.3 |
| | Literature review | §2.3 |
| | <u>Empirical Structural Validation</u> | |
| | Test example of transmission box | §3.1.3, Figure 3.4 |
| | Reconfigurable Machine Tool (RMT) | §6.1 |
| | Reconfigurable Inspection System (RIS) | §6.2 |
| | Application of RMT Configuration Design | §6.4.1 |
| | Application of RIS Configuration Design | §6.4.2 |
| | <u>Empirical Performance Validation</u> | |
| | Reconfigurable Manufacturing System (RMS) | §6.4 |
| | Application of RMS Configuration Design | §6.4.3 |

***Empirical Performance Validation.*** Reconfigurable Manufacturing System (RMS) is a reconfiguration strategy, a part of the computational framework, Design for Dynamic Management. Empirical performance validity of the RMS is performed in two steps (1) reconfiguration of a machine tool, and (2) reconfiguration of an inspection system. RMS is presented in Section 6.3. Empirical performance validation of the operability analysis is presented in Section 6.5.3.

## 7.3 Achievements, Contributions, and Limitations

The achievements and contributions of the dissertation are divided into three categories. The first contribution is adaptable concurrent design directly related to Hypothesis 1, Chapter 1, Section 1.4. Further, the adaptive concurrent design has a direct influence on decision-based design platform, particularly knowledge-based decision-based design ontology for multidisciplinary knowledge exchange, which will take place in future research presented Section 7.4.1. The second contribution is the operability analysis in the design of networked engineering systems directly related to Hypothesis 2, Chapter 1, Section 1.4. Further, operability analysis has a direct influence on decision-based design platform, particularly integrating producer and consumer needs in design, which will take place in future research presented Section 7.4.2. The third contribution is the reconfiguration strategy of networked engineering systems related to Hypothesis 3, Chapter 1, Section 1.4. Further, reconfiguration strategy takes decision-based design platform step forward in order to integrate any type of system in the platform, such as cyber-physical-social system, which will take place in future research presented Section 7.4.3.

### 7.3.1 Adaptive Concurrent Design of Networked Engineering Systems

***Expected Contributions related to Hypothesis 1.*** *Adaptable and Concurrent Design of Networked Engineering Systems*

- Identifying mechanical and control system drivers and their relations in concurrent design,
- Build in flexibility in selection and determination of values of design parameters in both systems,
- Managing the structure of the high-complexity mathematical problem,
- Creating effective and efficient decision network structure as a decision support, and
- Integration of process- and product-related decision models in the comprehensive model.

***Identified Limitation related to Hypothesis 1.*** *Adaptable and Concurrent Design of Networked Engineering Systems*

- Capture the information/knowledge in the design of networked engineering systems,

- Multidisciplinary knowledge exchange between different domains, beyond mechanical and control engineering, and
- Interfacing domain ontologies, converting different analogies between different domains in order to exchange knowledge between different users and make effective and efficient design decisions.

### 7.3.2 Operability Analysis of Networked Engineering Systems

***Expected Contributions related to Hypothesis 2.*** *Operability Analysis of Networked Engineering Systems*

- Framing operability and disturbance space without domain knowledge,
- Operability analysis of any engineering systems, and
- Managing dynamic performance of the system due to change in the requirements.

***Identified Limitations related to Hypothesis 2.*** *Operability Analysis of Networked Engineering Systems*

- Decision-based design templates for integrating consumer and producer preferences in system design, product and service system design,
- Managing dynamic performance of any system with change in the requirements, and
- Decision-based design decision-network for managing dynamic performance of any system with change in the requirements.

### 7.3.3 Reconfiguration Strategy of Networked Engineering Systems

***Expected Contributions related to Hypothesis 3.*** *Reconfiguration Strategy of Networked Engineering Systems*

- Strategy for Reconfiguration of Manufacturing System (RMS),

- Strategy for Reconfiguration of Manufacturing Tool (RMT), and
- Strategy for Reconfiguration of Inspection System (RIS).

***Identified Limitations related to Hypothesis 3.*** *Reconfiguration Strategy of Networked Engineering Systems*

- Allow multiple configurations of elements from different systems in the sustainable design of systems, product-service systems,
- Reach sustainability plateau by integrating cyber-physical-social systems in the design of systems, product-service systems, and
- Cyber-social design decision network in order to be sensitive to dynamic changes of consumer`s and producer`s preferences in the design of systems, product-service systems.

## 7.4 Future Work – Architecting Networked Engineering Systems Transition to Industry

Industry 4.0 is first presented at the Hanover Trade Fair in Germany 2011, as a transformative revolutionizing event where elements comprising industrial systems are interfaced with IoT to form Smart Factory (SF) of the future. However, there is a holistic picture of prolonged evolution behind it, Figure 7.2, as stressed out by Schaefer (Schaefer, 2017).

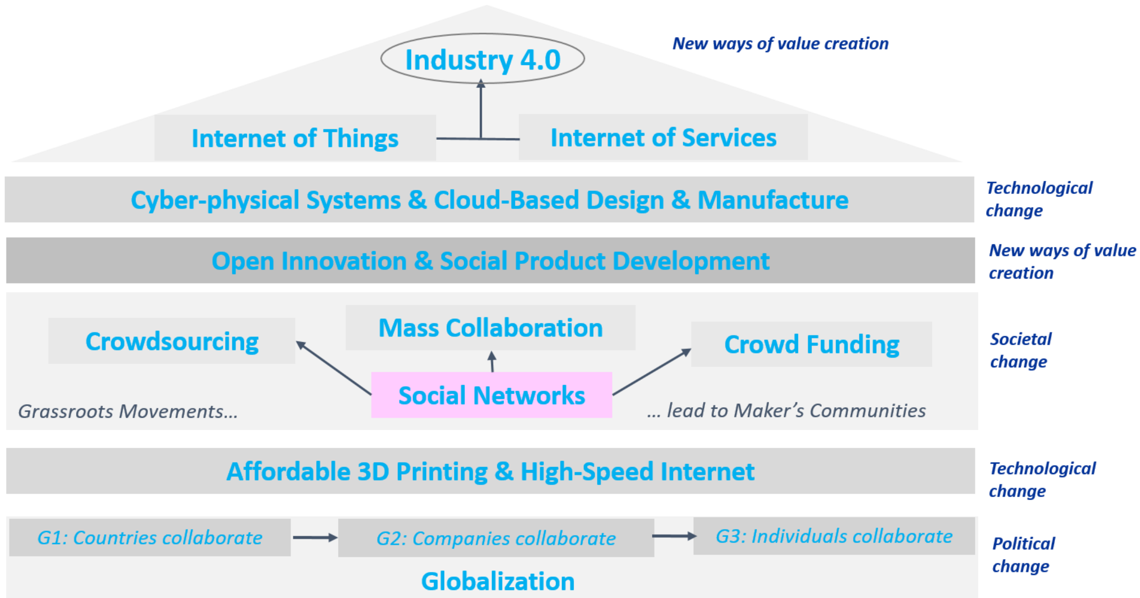



**Figure 7.2. The Evolution of Industry 4.0 (Schaefer, 2017)**

Political change in 90`s paved the way for a trend of globalization, which shifted from countries (G1 in Figure 7.2) to companies (G2 in Figure 7.2), and lastly to individuals (G3 in Figure 7.2) collaborations creating the environment for new business opportunities, the first row in Figure 7.2. Further, technological change in new millennium gave a major technological breakthrough with high-speed internet and affordable 3D printing, second row in Figure 7.2. Available and affordable high-speed internet lead social change, third row in Figure 7.2. Online social networks started to form and people joint forces to collaboratively conceive, design, build and test new products. Interconnected maker communities lead to new paradigms of crowdsourcing, mass collaboration, and crowdfunding. Industry soon realize the potential of this new talent pool and introduced Open Innovation practices and implemented Social Product Development tools as a new way to value creation, fourth row in Figure 7.2. Internet and communication technologies further advanced by the 2010s leading to a new technological breakthrough, one as the realization of Cloud Computing and second within the production engineering as Cloud-based Design and Manufacturing (CBDM).

***Trend of Product-Service-Systems and Cloud-based Design and Manufacturing.*** Enterprises are facing the joint challenges of mass customization and global competition, an increase in manufacturing-related services being provided by third-parties rather than in-house departments in order to stay competitive in the market.

The trend of new product-service-systems increased, especially in the area of data-driven design and manufacturing where smart sensor technology allow data gathering, analyzing, pro-active maintains and optimization production. This creates a need for model, digital twin, which will replicate the process based on use data from sensors installed on physical objects and represent their near real-time status, working condition or position.

The trend of Cloud-based Design and Manufacturing (CBDM) is a service-orientated product development model where consumers are enabled to configure, select, and utilize customized product ranging from Computer-Aided Design (CAD) software to Reconfigurable Manufacturing System (RMS) Schaefer (Schaefer, 2017). IoT and IoS play a major role and makes possible realization from conceptualization to production just based on consumer idea of a new product. There is a need for a model of a process, digital thread, to access information from operations and understand the process behind. Typical service-based cyber-physical product creation scenario is best explained by Schaefer (Schaefer, 2017), Figure 7.3.

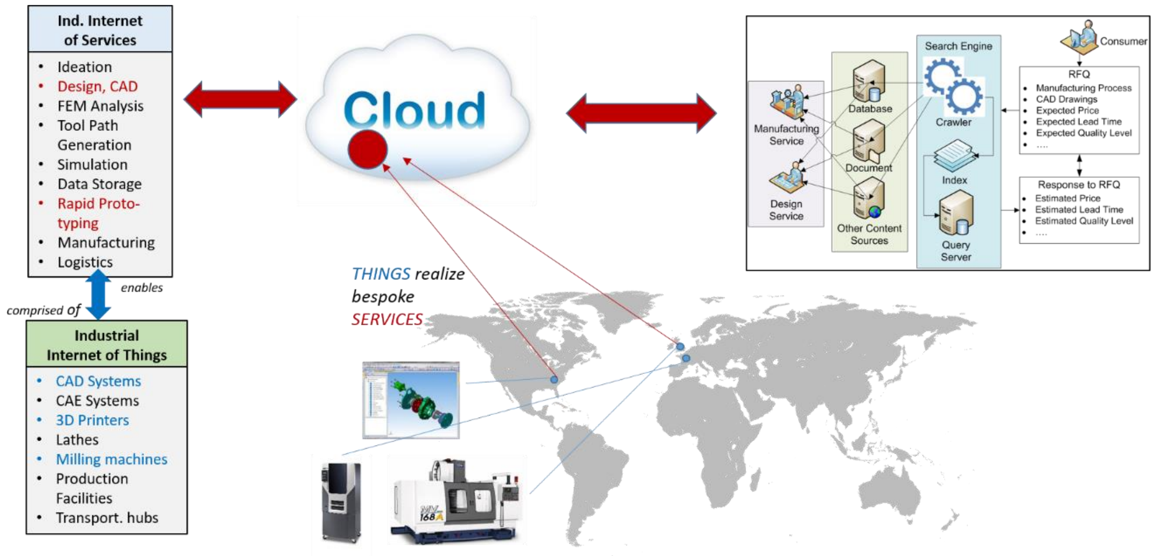



**Figure 7.3. A Service-oriented Cloud-based Design and Manufacturing Scenario (Schaefer, 2017)**

***Transition to Industry through Platformization.*** In this dissertation, it is recognized that a computational framework, Design for Dynamic Management, lies down a foundation for feedforward dynamic management of decision-based design and decision-based manufacturing and services, Figure 7.4, following the new trend of product-service-systems and cloud-based design and manufacturing. In decision-based design, manufacturing and services the information picked up by smart sensors feeds the model, digital twin. This information goes further in the model of a process, digital thread. In this way a designer has a chance to access information from operations, understand the process behind, perform solution space exploration and make design decisions. All this information/knowledge is captured in off-line model, an ontology, which gives us a chance to (re)use the knowledge for feedforward dynamic management in design, manufacturing and service processes.

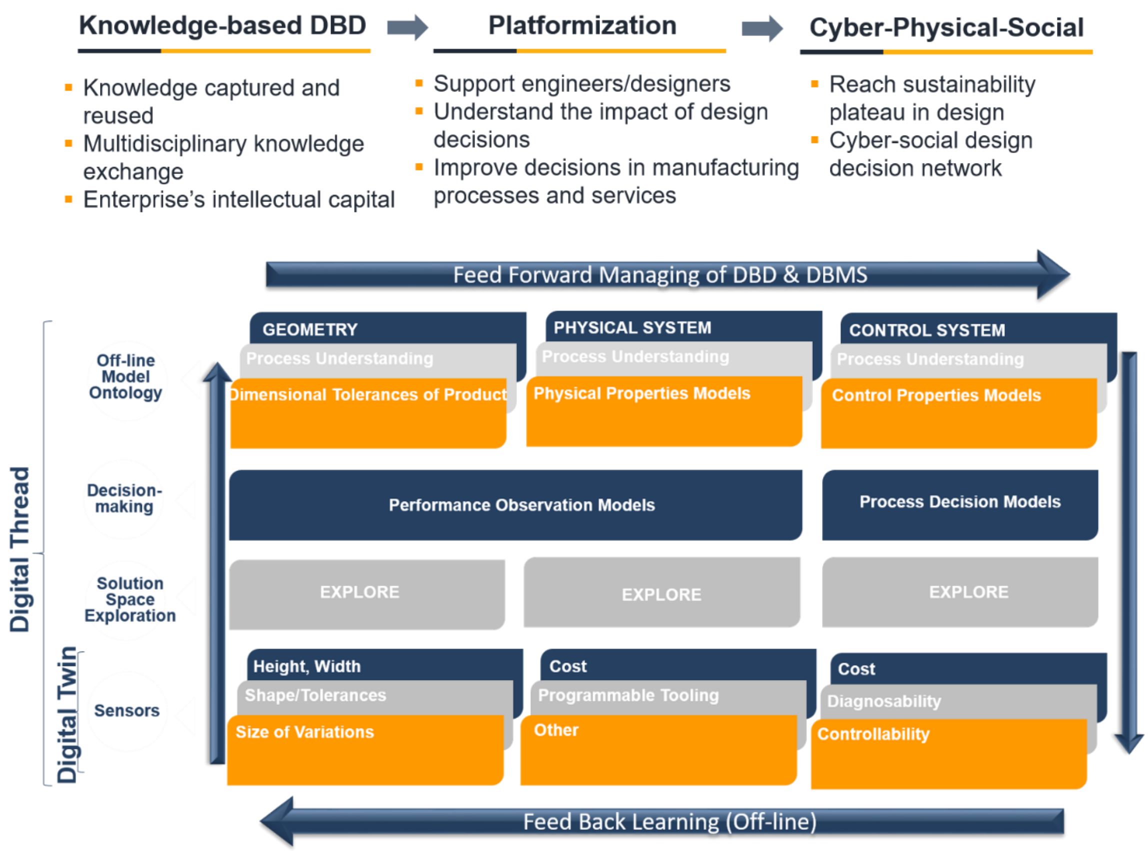



**Figure 7.4. Decision-Based Design, Manufacturing and Services**

***What are the Key Functionalities Needed?*** There is a need for (1) flexibility in design parameters; (2) design a system, product-service system insensitive to the different types of uncertainty and provide decision support without removing the sources; (3) "Satisficing" robust design solutions through solution space explorations and trade-offs; (4) goal-oriented, inverse, design exploration of production stages to achieve end performance goals and requirements of products; (5) operability analysis and accessing dynamic performance of a system; and (6) allow multiple reconfigurations between different elements in the system.

***What are the Requirements for Transition to Industry?*** There is a need for (1) integration of digital twin and digital thread; (2) the integration of models and simulation tools spanning processes and length scales (the different domains in axiomatic design);

(3) define computational workflows involving decision making, spanning multiple activities and users; (4) define modular, reusable sub-workflows for specific processes; (5) cyber-social design decision network; (6) ability to connect to external databases on materials, products, processes, and customer surveys; (7) knowledge-guided assistance to different types of users in design-related decision making; (8) collaborative, multidisciplinary design and privacy control (cyber security); (9) exploration of the design and solution space; and (10) dynamic and cost-efficient reconfiguration and integration of design decision templates to explore different robust design strategies.

***What is the Way Forward?*** Three steps are identified as a way forward.

- Step 1: Knowledge-Based Decision-Based Design Ontology, Section 7.4.1;
- Step 2: Decision-Based Design Platform, Section 7.4.2;
- Step 3: Integration of Cyber-Physical-Social Systems in the Platform, Section 7.4.3.

### 7.4.1. Knowledge-Based Decision-Based Design Ontology

Dynamic requirements of a global market are forcing engineering enterprises to pay closer attention to the design process underlying the process development. The value of the design process lies in that it constitutes a strategy for developing processes given a set of requirements which not only address current market needs but also accommodates impending changes, thus enhancing the agility of the enterprise to respond to dynamic markets. It is efficacious to capture and reuse the knowledge embedded in decisions made during the execution of a design process. Ontology is promising in modeling engineering knowledge for sharing and reuse.

The goal is to learn how knowledge can be captured and reused in the design of networked, multidisciplinary engineering systems. NES, such as Multistage Manufacturing Systems (MMPs), have both characteristics of a mechanical and a control system, typically designed separately. There is a concurrent design, and certain necessitates in the exchange of information are needed. Therefore, in this dissertation, a need for determining a taxonomy for both domains, interfacing the domain ontologies, and converting mechanical engineering into electrical engineering analogy in order to make effective and efficient decisions that can be utilized in the design of various multistage engineered systems is recognized. In further work, multidisciplinary knowledge exchange between mechanical, industrial and control engineering is considered in order to improve the design for dynamic management of NES.

The expected outcomes are the scientific and educational foundations of multidisciplinary knowledge exchange in the design of NES that will transform the way systems, product-service systems are designed and form a critical component of an enterprise's intellectual capital. These activities are expected to contribute to managing design processes among different disciplines by providing an ontology for capturing and reusing process-related knowledge associated with decision-based workflows using decision support problems (Ming, et al., 2017).

### 7.4.2. Decision-Based Design Platform

There is a need to automatize, reuse, and integrate knowledge between different users from different domains. In this dissertation, it is recognized that there is a need for a digital platform.

***What are the Identified Research Gaps?*** Three research gaps are identified in this dissertation that will be further addressed as the Step 2 of a way forward (1) decision-based design templates for integrating consumer and producer preferences in system design, product and service system design; (2) managing dynamic performance of any system with change in the requirements; and (3) decision-based design decision-network for managing dynamic performance of any system with change in the requirements.

***What is the Digital Platform Construct?*** The decision-based design digital platform construct consist of (1) Decision Support Problem constructs; (2) Decision Templates; and (3) Knowledge Management through the ontology.

### 7.4.3. Integration of Cyber-Physical-Social Systems in the Platform

Integration of Cyber-Physical-Social System in the digital platform to foster societal and technological innovations and reach symbiotic and sustainability design. Further, this gives a chance for collaborative design in large-scale (social) networks where a lot will be learned from analyzing communication and collaboration data, gaining new insights into Design Thinking research, and develop a great opportunity for Social Network Analysis and Big Data analytics.

***What are the Identified Research Gaps?*** Three research gaps are identified in this dissertation that will be further addressed as the Step 3 of a way forward (1) allow multiple configurations of elements from different systems in sustainable design of systems, product-service systems; (2) reach sustainability plateau by integrating cyber-physical-social systems in design of systems, product-service systems; and (3) cyber-social design decision network in order to be sensitive to dynamic changes of consumer`s and producer`s preferences in design of systems, product-service systems.

## 7.5 I Statement

In this section, I want to share my takeaways, leave a legacy for a future generation who want to create a new knowledge, become a toolmaker, and pursue a carrier in academia. This section has two parts, technical and personal.

### Technical Part

My dissertation is based on the philosophy that design is a decision-making process. Further, I believe that in the early stages of design uncertainty cannot be mitigated but rather managed when models are incomplete and incorrect. In my opinion, solution space exploration and locating ranges of good solutions have more sense than locating the best solution, especially in the design of complex systems.

In my dissertation, I propose a decision-based design computational framework, Design for Dynamic Management (DFDM), as a support to flexible, operable and rapidly configurable manufacturing processes. The DFDM has three critical components (1) adaptable concurrent design, (2) operability analysis, and (3) reconfiguration strategies. I will explain each of the DFDM components in turn by telling you story how I identified gaps, what are the contributions, and in the end, I will speculate how it can be used in setting new frontiers in Industry 4.0.

***Component 1.*** While working on my master thesis as a foundation to my doctoral dissertation I discovered that from the design of engineering systems depends on the quality of product and there is a need to design both a mechanical and a control concurrently in order to improve both system and the product quality. Further, my goal was not only to design a system of high-quality but to be diagnosable, controllable, and cost-effective. I did the extensive search of the literature (over 250 publications) and none of the existing methods allow flexibility in selection and determination of values of design parameters. Also, system diagnosability and controllability was observed separately. I identified these gaps are worth of investigation and I developed the Concurrent Design Exploration Method (CDEM) (Milisavljevic, et al., 2017). This method is based on the compromise decision support problem (cDSP) construct for the MMP where MMP is described by a Stream of Variation (SoV) model. The contributions are (1) concurrent method for the design of mechanical and control systems when the key design specifications are incomplete; (2) a systematic procedure to incorporate flexibility into system at the time of their design given uncertainty; (3) procedure to explore the solution space and identify system designs that are robust and provide insight into the effect of system parameters (positions for sensors, adequate numbers of sensors and sensing stations, and sensors distributions) on the dimensional quality and cost of the manufactured product; and (4) integrate the SoV approach from control theory with the cDSP construct in design of robust system and facilitate the analysis of the system prior to its implementation. In my doctoral dissertation, I went a step further and improve the CDEM to fit n-stage processes rather than a 3-stage manufacturing process and to be adaptable to dynamic changes. The improved method is named Adaptable Concurrent Realization of Networked Engineering Systems (ACRONES) (Milisavljevic-Syed, et al., 2018).

***Component 2.*** After consulting Dr. Gautham from TCS India I recognized the potential in operability and how its use can bridge the distance between design and control of systems. Further, I identified that the use of operability is limited to design of particular systems (chemical plant designs). In my dissertation, I decided to expand the use of operability and implement in the design of networked engineering systems (multistage manufacturing processes). I developed the Steady-State Operability Model (SSOM) that is integrated with the ACRONES (Milisavljevic-Syed, et al., 2018). The contributions are (1) expanding operability analysis to fit any engineering system rather than plant design; (2) framing the operability and disturbance spaces without prior domain knowledge by integrating it with the ACRONES; and (3) analyzing system functionality with change in the requirements in addition to disturbances. I went the step further and developed Dynamic Operability Model (DOM) (Milisavljevic-Syed, et al., 2018), integrated with the ACRONES and the SSOM, in order to determine the functionality of the system undergoing dynamic changes.

***Component 3.*** In collaboration with Xiwen Shang, MS student from the Beijing Institute of Technology, we identified that there is a need to design reconfigurable networked engineering systems. We recognized the need to maintain connectivity within the elements in the system at any time and in order to do so system needs to be reconfigurable, allow multiple configurations of elements within the system if connectivity is lost. In addition to Xiwen`s Tree-Based Decision Method for the Configuration Design of Reconfigurable Machine Tools (RMT) (Wang, et al., 2017) we developed Feature-Based Method for the Configuration Design of a Reconfigurable Inspection System (RIS) (Shang, et al., 2018), and A Method for Exploring the Systemic Reconfiguration Strategy of Reconfigurable Manufacturing System (RMS) (Shang, et al., 2018). The contributions are (1) expanding from the reconfiguration of a production line to reconfiguration of inspections system; and (2) combining the decision model (cDSP`s) with the interaction model (based on game theory) to form a decision network where the system reconfigurability and system diagnosability are ultimately maximized under limited cost.

My dissertation is fundamental research and way forward is transit to the industry where Decision-Based-Design Platform (DBDP) is a step in the right direction. Furthermore, I speculate that the impact will be transformative, making the step towards new frontiers in Industry 4.0. The DBDP will (1) provide support for making a decision between different users from different domains; (2) make possible feed forward dynamic management of design process, manufacturing, and services; and (3) a step forward into cyber-physical system design and manufacturing. I believe that sustainability can only be reached if we integrate cyber-physical-social system into the digital platform and the main requirement is to develop cyber-social-design-decision network.

## Personal Part

My dream is to become a professor and have a successful carrier in academia. In order to fulfill my dream, I decided to move from Europe, leave the University of Nis, Serbia, where I obtained my first MS, and leave my Ph.D. studies. I felt I was not prepared for life in academia instead I was educated to be an engineer, a tool user. Further, I decided to join the System Realization Laboratory (SRL) at the University of Oklahoma, USA and become a part of a big international academic family.

The SRL is researched orientated laboratory who foster new generation of professors who wants to become tool makers. In the SRL I learned how to create and archive knowledge, value scholarly work, teach, transmit and share knowledge. In the SRL I was constantly pushed out of my comfort zone which gave me a chance to develop career sustaining competencies (1) to continue learning through reflection and the associated creation and articulation of knowledge; (2) to speculate and identify gaps that foster innovation; (3) to ask questions, actively listen, reflect, and identify gaps and opportunities worthy of further investigation; (4) to make decisions using incomplete information; and (5) to think critically (deductive reasoning and inductive speculation) and identify a way forward. Further, I gained ability to undertake research on my own and develop multidisciplinary, international, sustainable, and external funded research programs. The competences I developed during my PhD studies are (1) ability to identify a research problem by defining a boundary around the area of interest; (2) ability to carry out literature search based on the boundary defined and frame a problem in terms of dilemmas that exists; (3) ability to pose questions worthy of investigation based on the identified dilemmas; (4) ability to propose a plan by identifying the associated tasks for addressing the questions posed; (5) ability to verify and validate the plan so that the knowledge gap is filled; and (6) ability to communicate a proposal for research.

In the SRL I actually learned how to write *scholarly* papers on my own. The papers I wrote prior to joining the SRL were associated with technical problem solving and development. In the SRL I have augmented my competency to write papers associated with practice to conceive and write scholarly research-related conference and high-quality journal papers. Further, I am in the final stages of submitting a proposal to CRC Press to publish my dissertation as a monograph. This is a testimony to my perseverance and my integrity in identifying, verifying and reporting my findings.

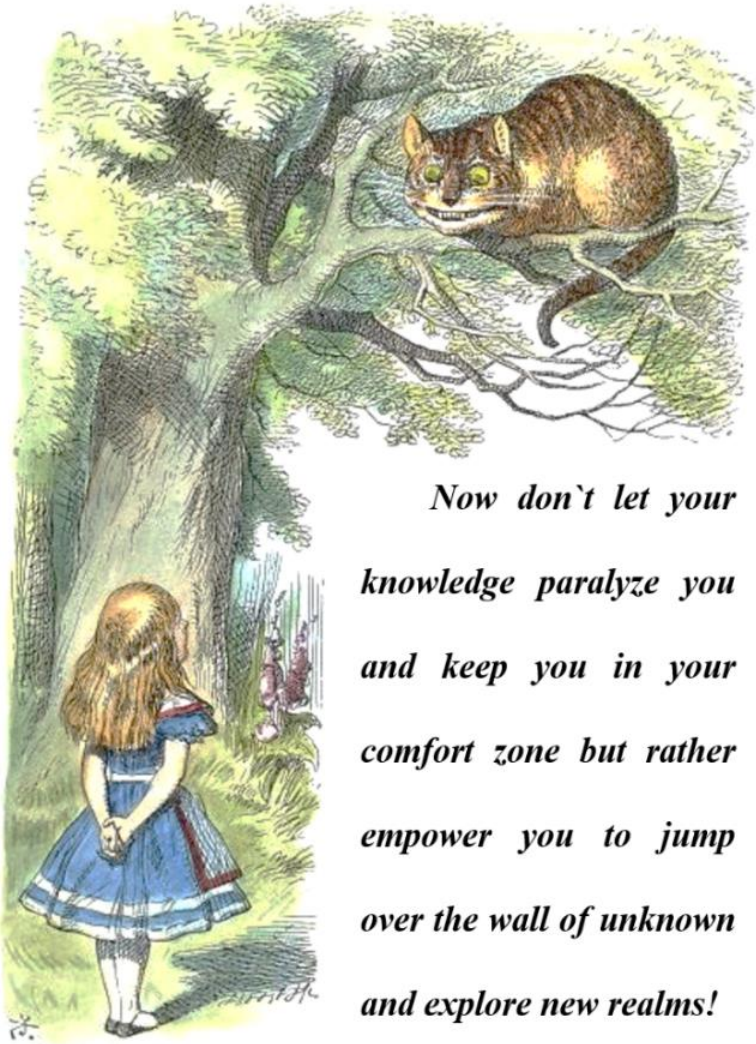



**Figure 7.5. A Personal Message from the Author**

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# Appendix A. Adaptable Concurrent Realization of Networked Engineering Systems (ACRONES)

In Appendix A results from process decision models (diagnosability, controllability, and cost-effectiveness), combined (DCE), and combined models under uncertainty, Quality, and Cost scenarios (DCER3_Q and DCER3_C) are presented.

**Table A.1. Solution Space of the Combined cDSP**

| Goal Function | Number of Sensors Distribution Schemes $M_{i,k}$ [-] | Total Number of Sensing Stations $M_S$ [-] | Total Number of Sensors $M_{Pi}$ [-] | Cost of the Process $C$ [$] | End-of-Process Variations $y_k$ [mm] |
|---|---|---|---|---|---|
| **G1** | 38 | 1 | 5 | 16 | 8.77E-06 |
| | 710 | 2 | | 17 | 1.20E-02 |
| | 832 | 3 | | 18 | 0.016088 |
| **Total** | 1580 | | | | |
| **G2** | 8 | 2 | 5 | 24 | 0.006343 |
| | 8 | 3 | | 26 | 0.006343 |
| **Total** | 16 | | | | |
| **G3** | 8 | 2 | 5 | 36 | 8.77E-06 |
| | 8 | 3 | | 39 | 0.012677 |
| **Total** | 16 | | | | |

The solution space of diagnosability (G1), controllability (G2), and cost-effectiveness (G3) models are presented in Table A.1. The solution space of each of the models is characterized by (1) the number of sensors distribution schemes, $M_{i,k}$, the total number of sensing stations, $M_S$, the total number of sensors, $M_{Pi}$, the cost of the process, $C$. The size of end-of-line variations, $y_k$, is checked through the performance measurement model for all these three models G1 – G3.

The solution space of the combined DCE model is presented in Table A.2. The solution space of the combined model is characterized by (1) the number of sensors distribution schemes, $M_{i,k}$, the total number of sensing stations, $M_S$, the total number of sensors, $M_{Pi}$, the cost of the process, $C$. The size of end-of-line variations, $y_k$, is checked through the performance measurement model for the combined model DCE.

**Table A.2. Solution Space of DCE**

| Number of Sensors Distribution Schemes $M_{i,k}$ [-] | Total Number of Sensing Stations $M_S$ [-] | Total Number of Sensors $M_{Pi}$ [-] | Cost of the Process $C$ [$] | Range of End-of-Process Variations $y_k$ [mm] |
|---|---|---|---|---|
| 1 | | 4 | 26 | 2.56E-06 |
| 8 | | 5 | 31 | 2.56E-06 – 0.011195 |
| 28 | | 6 | 36 | 2.59E-06 – 0.011261 |
| 56 | | 7 | 41 | 3.00E-06 – 0.011263 |
| 70 | 2 | 8 | 46 | 3.05E-06 – 0.011264 |
| 56 | | 9 | 51 | 3.50E-06 – 0.011264 |
| 28 | | 10 | 56 | 5.18E-06 – 0.011264 |
| 8 | | 11 | 61 | 7.19E-06 – 0.011264 |
| 1 | | 12 | 66 | 0.011264 |
| Total 256 | | | | |
| 8 | | 5 | 34 | 2.56E-06 |
| 92 | | 6 | 39 | 2.56E-06 – 0.011195 |
| 504 | | 7 | 44 | 2.56E-06 – 0.011261 |
| 1750 | | 8 | 49 | 2.56E-06 – 0.011263 |
| 4312 | | 9 | 54 | 2.56E-06 – 0.011264 |
| 7980 | | 10 | 59 | 2.56E-06 – 0.011264 |
| 11432 | | 11 | 64 | 2.56E-06 – 0.011264 |
| 12869 | | 12 | 69 | 2.56E-06 – 0.011264 |
| 11440 | 3 | 13 | 74 | 2.57E-06 – 0.011264 |
| 8008 | | 14 | 79 | 2.59E-06 – 0.011264 |
| 4368 | | 15 | 84 | 3.01E-06 – 0.011264 |
| 1820 | | 16 | 89 | 3.06E-06 – 0.011264 |
| 560 | | 17 | 94 | 3.50E-06 – 0.011264 |
| 120 | | 18 | 99 | 5.19E-06 – 0.011264 |
| 16 | | 19 | 104 | 7.19E-05 – 0.011264 |
| 1 | | 20 | 109 | 0.011264 |
| Total 65280 | | | | |

**Table A.3. Solution Space of DCER3_Q**

| Number of Sensors Distribution Schemes $M_{i,k}$ [-] | Total Number of Sensing Stations $M_S$ [-] | Total Number of Sensors $M_{Pi}$ [-] | Cost of the Process $C$ [$] | Range of End-of-Process Variations $y_k$ [mm] |
|---|---|---|---|---|
| 1 | 2 | 5 | 30 | 2.56E-06 |
| 6 | | 6 | 35 | 2.59E-06 – 0.011195 |
| 15 | | 7 | 40 | 3.02E-06 – 0.011261 |
| 20 | | 8 | 45 | 3.49E-06 – 0.011263 |
| 15 | | 9 | 50 | 5.17E-06 – 0.011264 |
| 6 | | 10 | 55 | 7.19E-05 – 0.011264 |
| 1 | | 11 | 60 | 0.011264 |
| Total 64 | | | | |
| 8 | 3 | 6 | 37 | 2.56E-06 – 2.57E-06 |
| 76 | | 7 | 42 | 2.56E-06 – 0.011195 |
| 344 | | 8 | 47 | 2.56E-06 – 0.011261 |
| 986 | | 9 | 52 | 2.56E-06 – 0.011263 |
| 1996 | | 10 | 57 | 2.56E-06 – 0.011264 |
| 3002 | | 11 | 62 | 2.56E-06 – 0.011264 |
| 3432 | | 12 | 67 | 2.56E-06 – 0.011264 |
| 3003 | | 13 | 72 | 2.57E-06 – 0.011264 |
| 2002 | | 14 | 77 | 2.60E-06 – 0.011264 |
| 1001 | | 15 | 82 | 3.03E-06 – 0.011264 |
| 364 | | 16 | 87 | 3.50E-06 – 0.011264 |
| 91 | | 17 | 92 | 5.19E-06 – 0.011264 |
| 14 | | 18 | 97 | 7.19E-05 – 0.011264 |
| 1 | | 19 | 102 | 0.011264 |
| Total 16320 | | | | |

The solution space of the combined model under uncertainty Type III, Quality scenario, DCER3_Q is presented in Table A.3. The solution space of the combined model is characterized by (1) the number of sensors distribution schemes, $M_{i,k}$, the total number of sensing stations, $M_S$, the total number of sensors, $M_{Pi}$, the cost of the process, $C$. The size of end-of-line variations, $y_k$, is checked through the performance measurement model for the combined model under uncertainty Type III, Quality scenario, DCER3_Q.

The solution space of the combined model under uncertainty Type III, Cost scenario, DCER3_C is presented in Table A.4. The solution space of the combined model is characterized by (1) the number of sensors distribution schemes, $M_{i,k}$, the total number of sensing stations, $M_S$, the total number of sensors, $M_{Pi}$, the cost of the process, $C$. The size of end-of-line variations, $y_k$, is checked through the performance measurement model for the combined model under uncertainty Type III, Cost scenario, DCER3_C.

**Table A.4. Solution Space of DCER3_C**

| Number of Sensors Distribution Schemes $M_{i,k}$ [-] | Total Number of Sensing Stations $M_S$ [-] | Total Number of Sensors $M_{Pi}$ [-] | Cost of the Process $C$ [$] | Range of End-of-Process Variations $y_k$ [mm] |
|---|---|---|---|---|
| 1 | 2 | 4 | 19 | 2.57E-06 |
| 7 | | 5 | 23 | 2.60E-06 – 0.011195 |
| Total 8 | | | | |
| 8 | 3 | 5 | 23 | 2.59E-06 – 2.60E-06 |
| Total 8 | | | | |

# Appendix B. Panel Stamping Process Description

In Appendix B, Stream of Variation (SoV) model and state matrices for 2-D Panel Assembling Process in N - Stations is presented. System variable selection and specifications are presented. Operability spaces of a panel stamping process is presented. Lastly, the cDSP construct for the Steady-State Operability Analysis of a panel stamping process is presented.

## Stream of Variation (SoV) Model

Dimensional SoV model is primarily developed for multistage assembly and machining processes. Fixture locators are tools in the assembling process used at each stage of the process that manages dimensional quality of a product. The propagation of fixtures variation contributed from each station and its impact on the final product quality are described by the stream-of-variation model (Jin, et al., 1999):

$$X_i = A_{i-1} \cdot X_{i-1} + B_i \cdot U_i + V_i \tag{B.1}$$

$$Y_i = C_i \cdot X_i + W_i \tag{B.2}$$

The Equation B.1 is the state equation, which implies that part variation at Station *i* is influenced by two sources: (1) the accumulated variation up to Station *i*-1, and (2) the variation on Station *i*. The Equation B.2 is the observation equation. For further information about the system matrices see (Jin, et al., 1999).

### *State Matrices for 2-D Panel Assembling Process in N – Stations*

***Dynamic Matrix A.*** If the fixture locating scheme is unchanged in the consecutive stations, e.g., several features are machined by using the same datum in a multi-station machining operation then the dynamic matrix is equal to the unit matrix. However, if a part is positioned by a new set of fixtures, the part will be reoriented on a new fixture set and the dynamic matrix is equal to. For the development of dynamic matrix see Jin and co-authors (Jin, et al., 1999). The difference between three stage and four stage panel stamping processes is the number of dynamic matrices A.

Transfer matrix:

$$T(i-1) = \begin{pmatrix} H(i) & \Theta \\ \Theta & \Theta \end{pmatrix} \tag{B.3}$$

If fixture locators $P_1$ and $P_2$ are on the different Parts *i* and *j* then assembly transfer matrix is:

$$H(i) = [H_{ri}(i) \quad \Theta \quad H_{ji}(i)] \tag{B.4}$$

If fixture locators $P_1$ and $P_2$ are on the same Part *i* then assembly transfer matrix is:

$$H(i) = [\Theta \quad -M_{i,i}(i) \quad \Theta] \tag{B.5}$$

Subassembly transfer matrix, between Parts *r* and *i*:

$$H_{ri}(i) = M_{Ar,P1}(i) \cdot D(i) \cdot M_{P1,Aj}(i) \tag{B.6}$$

Subassembly transfer matrix, between Parts *j* and *i*:

$$H_{rj}(i) = M_{Ar,P1}(i) \cdot G(i) \cdot M_{P2,Aj}(i) \tag{B.7}$$

Transformation matrix gives the deviation relationship between the two points of part point $A_r$ and locator point $P_1$:

$$M_{Ar,P1}(i) = \begin{pmatrix} 1 & 0 & -L_Z(P_1, A_r) \\ 0 & 1 & L_x(P_1, A_r) \\ 0 & 0 & 1 \end{pmatrix} \tag{B.8}$$

Deviation matrix gives the deviation between fixture points $P_1$ and $P_2$:

$$D(i) = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & \frac{1}{L_X(P_1, P_2)} & 0 \end{pmatrix} \tag{B.9}$$

Transformation matrix gives the deviation relationship between the two points of part point $A_j$ and locator point $P_1$:

$$M_{P1,Aj}(i) = \begin{pmatrix} 1 & 0 & -L_Z(A_j, P_1) \\ 0 & 1 & L_x(A_j, P_1) \\ 0 & 0 & 1 \end{pmatrix} \tag{B.10}$$

Deviation matrix gives deviation between fixture points $P_1$ and $P_2$:

$$G(i) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -\dfrac{1}{L_X(P_1, P_2\,)} & 0 \end{pmatrix} \tag{B.11}$$

Transformation matrix gives the deviation relationship between the two points of part point $A_j$ and locator point $P_2$:

$$M_{P2,Aj}(i) = \begin{pmatrix} 1 & 0 & -L_Z(A_j, P_2) \\ 0 & 1 & L_x(A_j, P_2) \\ 0 & 0 & 1 \end{pmatrix} \tag{B.12}$$

Dynamic matrix $A_1(2)$ represent assembly of Parts 1 and 2 that are coming from Station 1 to Station 2, see Equation B.13:

$$A_1(2) = \begin{bmatrix} A_{11} & \cdots & A_{14} \\ \vdots & \ddots & \vdots \\ A_{41} & \cdots & A_{44} \end{bmatrix}_{12\times12} \tag{B.13}$$

Dynamic matrix $A_2(3)$ represent subassembly Parts 1 and 2, and Part 3 that are coming from Station 2 to Station 3, see Equation B.14:

$$A_2(3) = \begin{bmatrix} A_{11} & \cdots & A_{14} \\ \vdots & \ddots & \vdots \\ A_{41} & \cdots & A_{44} \end{bmatrix}_{12\times12} \tag{B.14}$$

Dynamic matrix $A_3(4)$ represent subassembly Parts 1,2 and 3, and Part 4 that are coming from Station 3 to Station 4, see Equation B.15. Dynamic matrix $A_3$ can be found in four stage processes.

$$A_3(4) = \begin{bmatrix} A_{11} & \cdots & A_{14} \\ \vdots & \ddots & \vdots \\ A_{41} & \cdots & A_{44} \end{bmatrix}_{12\times 12} \tag{B.15}$$

***Input Matrix B.*** Matrix $B_i$ is the input matrix which determines how fixture deviation affects part deviation on Station *i*, based on the geometry of a fixture locating layout (Jin, et al., 1999). The rank of $B_i$ equals to the number of degrees of freedom d.o.f. of the supported workpieces restrained by the fixture set. The difference between three stage and four stage panel stamping processes is the number and size of input matrices B. Input matrix for Station *i*:

$$B(i) = \begin{pmatrix} Q_{A_1,P_1} & \Theta \\ \vdots & \vdots \\ Q_{A_i,P_1} & \Theta \\ \Theta & Q_{A_{i+1},P_1} \\ \Theta & \Theta \end{pmatrix} \tag{B.16}$$

Coordinate transformation matrix from the fixture error to the part locating error represented by the part point $A_i$ at Station i:

$$Q_{A_i,P_1} = \begin{pmatrix} 1 & \frac{L_Z(A,P_1)}{L_X(P_1,P_2)} & -\frac{L_Z(A,P_1)}{L_X(P_1,P_2)} \\ 0 & 1-\frac{L_Z(A,P_1)}{L_X(P_1,P_2)} & \frac{L_Z(A,P_1)}{L_X(P_1,P_2)} \\ 0 & -\frac{1}{L_X(P_1,P_2)} & \frac{1}{L_X(P_1,P_2)} \end{pmatrix} \tag{B.17}$$

where

$L_X(P_1,P_2) = x_{P_2} - x_{P_1}$ : coordinate points $P_1$ and $P_2$ in the body coordinate in the *x*-direction,

$L_Z(P_1,P_2) = z_{P_2} - z_{P_1}$ : coordinate points $P_1$ and $P_2$ in the body coordinate in the *z*-direction.

Input matrix $B_1(1)$ for Station 1, see Equation B.18:

$$B_1(1) = \begin{bmatrix} B_{11} & \cdots & B_{12} \\ \vdots & \ddots & \vdots \\ B_{41} & \cdots & B_{42} \end{bmatrix}_{12\times 6} \tag{B.18}$$

Input matrix $B_2(2)$ for Station 2, see Equation B.19:

$$B_2(2) = \begin{bmatrix} B_{11} & \cdots & B_{12} \\ \vdots & \ddots & \vdots \\ B_{41} & \cdots & B_{42} \end{bmatrix}_{12\times i} \tag{B.19}$$

where

$i = 9$ : in case of 3-stage process,
$i = 6$ : in case of 4-stage process.

Input matrix $B_3(3)$ for Station 3, see Equation B.20:

$$B_3(3) = \begin{bmatrix} B_{11} & \cdots & B_{12} \\ \vdots & \ddots & \vdots \\ B_{41} & \cdots & B_{42} \end{bmatrix}_{12\times i} \tag{B.20}$$

where

$i = 3$ : in case of 3-stage process,
$i = 6$ : in case of 4-stage process.

Input matrix $B_4(4)$ for Station 4, see Equation B.21:

$$B_4(4) = \begin{bmatrix} B_{11} \\ \vdots \\ B_{41} \end{bmatrix}_{12x3} \tag{B.21}$$

***Control Matrix C.*** Matrix $C_i$ contains the information about sensor locations on a station. When sensors are installed on one or more stations in a production line, the index for the observation Equation 2 is actually a subset of 1,2, . . . ,N, whereas the index for the state Equation 1 is the complete set (Jin, et al., 1999). Similarly, the rank of $C_i$ corresponds to the number of measured degrees of freedom of a part or a subassembly on Station *i*.

Control matrix for Station *i*:

$$C(i) = \begin{pmatrix} C_1(i) & \cdots & \Theta \\ \vdots & \ddots & \vdots \\ \Theta & \cdots & C_n(i) \end{pmatrix} \tag{B.21}$$

Sub-matrix for Station *i*:

$$C_r(i) = \begin{pmatrix} 1 & 0 & -L_Z(R_{1,r}, A_r) \\ 0 & 1 & L_X(R_{1,r}, A_r) \\ \vdots & \vdots & \vdots \\ 1 & 0 & -L_Z(R_{m_r,r}, A_r) \\ 0 & 1 & L_X(R_{m_r,r}, A_r) \end{pmatrix}_{(2\cdot m_r)\times 3} \qquad \text{(B.22)}$$

where

$L_X(R_{m_r,r}, A_r) = x_{A_r} - x_{R_{m_r,r}}$ : distance between first part point $A_r$ in the part and measurement point $m_r$ in x direction,

$L_Z(R_{m_r,r}, A_r) = z_{A_r} - z_{R_{m_r,r}}$ : distance between first part point $A_r$ in the part and measurement point $m_r$ in $z$ direction.

Control matrix $C(3)$ for end-of-line sensing distribution scheme in three stage process in the measurement station is the following, see Equation B.23.

$$C(3) = \begin{bmatrix} C_{11} & \cdots & C_{14} \\ \vdots & \ddots & \vdots \\ C_{41} & \cdots & C_{44} \end{bmatrix}_{16x12} \qquad \text{(B.23)}$$

Control matrix $C(4)$ for end-of-line sensing distribution scheme in four stage process in the measurement station is the following, see Equation B.24.

$$C(4) = \begin{bmatrix} C_{11} & \cdots & C_{14} \\ \vdots & \ddots & \vdots \\ C_{41} & \cdots & C_{44} \end{bmatrix}_{16\times 12} \qquad \text{(B.24)}$$

Control matrix $C_1(1)$ for distributed sensing distribution scheme in three stage process in the first station is the following, see Equation B.25:

$$C_1(1) = \begin{bmatrix} C_{11} & \cdots & C_{14} \\ \vdots & \ddots & \vdots \\ C_{21} & \cdots & C_{24} \end{bmatrix}_{8x12} \qquad \text{(B.25)}$$

Control matrix $C_2(2)$ for distributed sensing distribution scheme in n- stage process in the second station is the following, see Equation B.26:

$$C_2(2) = \begin{bmatrix} C_{11} & \cdots & C_{14} \\ \vdots & \ddots & \vdots \\ C_{41} & \cdots & C_{44} \end{bmatrix}_{ix12} \qquad \text{(A.26)}$$

where

$i = 16$ : in case of 3-stage process,
$i = 12$ : in case of 4-stage process.

Control matrix $C_3(3)$ for distributed sensing distribution scheme in n-stage process in the third station is the following, see Equation B.27:

$$C_3(3) = \begin{bmatrix} C_{11} & \cdots & C_{14} \\ \vdots & \ddots & \vdots \\ C_{41} & \cdots & C_{44} \end{bmatrix}_{16x12} \tag{B.27}$$

Control matrix $C_4(4)$ for distributed sensing distribution scheme in four stage process in the fourth station is the following, see Equation B.28:

$$C_4(4) = \begin{bmatrix} C_{11} & \cdots & C_{14} \\ \vdots & \ddots & \vdots \\ C_{41} & \cdots & C_{44} \end{bmatrix}_{16x12} \tag{B.28}$$

*System Variable Selection and Specifications*

Cost of the process is function of total number of sensors $M_i$ and sensing stations $M_S$ in the process, see Equation B.29:

$$C = M_i + M_S \tag{B.29}$$

Total number of sensing stations in the process is sum of actual number of sensors over potential number of sensors at Station k. If there are no sensors at station *k* than there is no sensing station $M_{S,k}$ at a particular station *k*. If there is at least one sensor than there is sensing station $M_{S,k}$ at station *k*. Mathematical formulation is the following:

$$M_S = \sum_{k=1}^{n} \sum_{i=1}^{m} \frac{M_i}{M_{pi}} \text{ given that } \frac{M_i}{M_{pi}} \begin{cases} = 0 \\ > 0 \end{cases} \text{ then } M_{S,k} \begin{cases} 0 \\ 1 \end{cases} \tag{B.30}$$

Total number of sensing stations depends on sensor distribution scheme $M_{i,k}$. In case of *end-of-line* sensing the total number of sensing stations is $0 \leq M_S \leq 1$, and for *distributed* sensing it is $0 \leq M_S \leq N$ (*N* is the number of operational stations).

Sensors distribution scheme present how actual number of sensors $M_i$ is is distributed throughout the stations in the process. It is different for *end-of-line* and *distributed* sensing, see Equation B.31:

Distributed Sensing — End-of-Line Sensing

$$\begin{array}{cc} M_1 = M_{1,1} + M_{2,1} + \cdots + M_{i,1} & M_1 = 0 \\ \vdots & \vdots \\ M_m = M_{i+1,m} + M_{i+2,m} + \cdots + M_{n,m} & M_m = M_{1,m} + M_{2,m} + \cdots + M_{n,m} \end{array} \tag{B.31}$$

where

$M_i = M_1 + \cdots + M_n = \sum_{k=1}^{n}\sum_{i=1}^{m} M_{i,k}$ : total number of sensors.

**Table B.1. Panel Stamping Process Design Parameters**

| Fixture Points | Coordinate in *x*- direction [mm] | Coordinate in *z*- direction [mm] |
|---|---|---|
| $P_1$ | 63.0 | 50.0 |
| $P_2$ | 800.0 | 50.0 |
| $P_3$ | 1019.0 | 50.0 |
| $P_4$ | 1312.0 | 50.0 |
| $P_5$ | 1688.0 | 470.0 |
| $P_6$ | 2005.0 | 470.0 |
| $P_7$ | 1688.0 | 50.0 |
| $P_8$ | 2005.0 | 50.0 |
| **Sensor Points** | **Coordinate in *x*- direction [mm]** | **Coordinate in *z*- direction [mm]** |
| M1 | 0.0 | 600.0 |
| M2 | 950.0 | 0.0 |
| M3 | 950.0 | -300.0 |
| M4 | 1630.0 | 800.0 |
| M5 | 0.0 | 0.0 |
| M6 | 950.0 | 600.0 |
| M7 | 950.0 | -300.0 |
| M8 | 1630.0 | 800.0 |
| M9 | 1630.0 | 300.0 |
| M10 | 2310.0 | 700.0 |
| M11 | 1630.0 | -150.0 |
| M12 | 2310.0 | 200.0 |
| M13 | 0.0 | 0.0 |
| M14 | 950.0 | 600.0 |
| M15 | 950.0 | -300.0 |
| M16 | 1630.0 | 800.0 |
| M17 | 1630.0 | 300.0 |
| M18 | 2310.0 | 700.0 |
| M19 | 1630.0 | -150.0 |
| M20 | 2310.0 | 200.0 |

**Table B.2. Available Input Space (AIS)**

| Symbol | Description | Lower Bound | Upper Bound | Units |
|---|---|---|---|---|
| $P_i$ | total number of fixture points | 0 | 8 | [−] |
| $M_{Pi}$ | potential number of sensors | 0 | 20 | [−] |
| $P_{i_{x,z}}$ | potential position of tools | 0 | 2005 | [mm] |
| $M_{i_{x,z}}$ | potential position of sensors | 0 | 2310 | [mm] |
| $M_{i,k}$ | potential distribution of sensors per station | 0 | 8 | [-] |
| $\sum V$ | sensor noise covariance | 0.0009· I | 0.009· I | $[\mathrm{mm}^2]$ |
| $\sum W$ | disturbances covariance | 0.0001· I | 0.001· I | $[\mathrm{mm}^2]$ |

**Table B.3. Desired Output Space (DOS)**

| Symbol | Description | Lower Bound | Upper Bound | Units |
|---|---|---|---|---|
| Cost | overall cost | 0 | n | [$] |
| $y_k$ | dimensional variations at station | -0.8 | 0.8 | [mm] |
| $M_i$ | total number of sensors | 0 | n | [-] |
| $M_{i,k}$ | distribution of sensors per station | 0 | n | [-] |
| $M_S$ | total number of sensing stations | 0 | n | [-] |

**Table B.4. Expected Disturbance Space (EDS)**

| Symbol | Description | Lower Bound | Upper Bound | Units |
|---|---|---|---|---|
| $X_1 \pm 3\sigma$ | natural uncertainty (sensor noise) | -0.0013 | 0.0013 | [mm] |
| $X_2 \pm 3\sigma$ | natural uncertainty (process disturbance) | -0.0014 | 0.0014 | [mm] |
| $P_{i_{x,z}} \pm \Delta X_1$ | model parameter uncertainty (variation in fixture position) | $0 \pm 15$ | $2005 \pm 15$ | [mm] |
| $M_{i_{x,z}} \pm \Delta X_2$ | model parameter uncertainty (variation in sensor position) | $0 \pm 25$ | $2310 \pm 25$ | [mm] |

**Operability Spaces of a Panel Stamping Process**

***Achievable Output Space (AOS).*** Achievable Output Space (AOS*)* is the collection of output points achieved by solving the model for the entire Available Input Space (AIS). AOS is a function of $u$ and $d$, $AOS_u(d^N)$ where AOS is calculated by considering all the points inside the AIS, denoted by the subscript $u$, when the disturbances are at their nominal values, $d^N$. AOS are the output values achieved by solving comprehensive model (DCE) of panel stamping process.

Mathematical formulation of AOS is the following:

$$AOS = \bigcup_{u \in AIS} AOS_u(d^N) \tag{B.32}$$

Thus in panel stamping process, input points of AOS is studied as a function of the identified variables, see Table B.2:

$$u = f\left(P_i, M_i, P_{i_{x,z}}, M_{i_{x,z}}\right) \tag{B.33}$$

where disturbances, at their nominal values, is the function of sensor noise and process disturbances covariance:

$$d^N = f\left(\sum V, \sum W\right) \tag{B.34}$$

Mathematical formulation of AOS in the panel stamping process is the following:

$$AOS = \bigcup_{u \in AIS} AOS_{\left(P_i, M_i, P_{i_{x,z}}, M_{i_{x,z}}\right)}\left(\sum V, \sum W\right) \tag{B.35}$$

***Desired Output Space (DOS).*** Desired Output Space (DOS) is desired operating window for the process outputs. DOS is defined by designer as their wish for achieving certain output space.

Mathematical formulation of DOS is the following:

$$DOS = \bigcup DOS_d(y) \tag{B.36}$$

Thus in panel stamping process, output points of DOS is studied as a function of the identified variables, see Table B.2:

$$y = f\left( M_i, M_{i,k}, M_{Si}, C, y_k\right) \tag{B.37}$$

Mathematical formulation of DOS in the panel stamping process is the following:

$$DOS = \bigcup DOS_d\left(M_i, M_{i,k}, M_{Si}, C, y_k\right) \tag{B.38}$$

***Available Input Space (AIS).*** Available Input Space (AIS) is inputs of the process able to change over a certain range. AIS are the input points available by exercising ACRONES or through prior designer knowledge, i.e., design experience.

Mathematical formulation of AIS is the following:

$$AIS = \bigcup AIS_d(u) \tag{B.39}$$

Thus in panel stamping process, input points of AIS are studied as a function of the variables identified with ACRONES, see Table B.1:

$$u = f\left(P_i, M_i, P_{i_{x,z}}, M_{i_{x,z}}, M_{i,k}, \sum V, \sum W\right) \tag{B.40}$$

Mathematical formulation of AIS in the panel stamping process is the following:

$$AIS = \bigcup AIS_d\left(P_i, M_i, P_{i_{x,z}}, M_{i_{x,z}}, M_{i,k}, \sum V, \sum W\right) \tag{B.41}$$

***Desired Input Space (DIS).*** Desired Input Space (DIS) is the set of input values required to reach the entire DOS. The total Desired Input Space defined as the union of $DIS_d(y)$ for all $y$ in DOS, or the union of $DIS_y(d)$ for all $d$ in EDS. For example, in panel stamping process if we want to reach certain output (cost) of process we need to adjust points in DIS accordingly.

Mathematical formulation of DIS is the following:

$$DIS = \bigcup_{y \in DOS} DIS_d(y) = \bigcup_{d \in EDS} DIS_y(d) \tag{B.42}$$

In the panel stamping process, input points that need to be adjusted $u \in AIS$, see Equation A.37, in order to reach the output points $y \in DOS$, see Equation A.34. Mathematical formulation of DIS in the panel stamping process is the following:

$$DIS = \bigcup_{y \in DOS} DIS_d\left(M_i, M_{i,k}, M_{Si}, C, y_k\right)$$

$$= \bigcup_{d \in EDS} DIS_y\left(\mathrm{x}_1 \pm 3\sigma, \mathrm{x}_2 \pm 3\sigma \;\; P_{i_{x,z}} \pm \Delta \mathrm{X}_1, M_{i_{x,z}} \pm \Delta \mathrm{X}_2\right) \quad \text{(B.43)}$$

***Tolerable Disturbance Space (TDS).*** Tolerable Disturbance Space (TDS) are region of disturbances that can be tolerated with the available inputs AIS, keeping the system at the nominal operating point. TDS is determined only for the existing system design. In panel stamping process, TDS is determined by exercising ACRONES.

Mathematical formulation of TDS is the following:

$$TDS = \bigcup_{d \in TDS} AIS_u(d) \quad \text{(B.44)}$$

Thus in panel stamping process, expected disturbances $d$ in AIS are studied as a function of the variables identified with ACRONES:

$$d = f\left(\mathrm{x}_1 \pm 3\sigma, \mathrm{x}_2 \pm 3\sigma \;\; P_{i_{x,z}} \pm \Delta \mathrm{X}_1, M_{i_{x,z}} \pm \Delta \mathrm{X}_2\right) \quad \text{(B.45)}$$

Mathematical formulation of TDS in the panel stamping process is the following:

$$TDS = \bigcup_{d \in TDS} AIS_u\left(\mathrm{X}_1 \pm 3\sigma, \mathrm{X}_2 \pm 3\sigma \;\; P_{i_{x,z}} \pm \Delta \mathrm{X}_1, M_{i_{x,z}} \pm \Delta \mathrm{X}_2\right) \quad \text{(B.46)}$$

***Expected Disturbance Space (EDS).*** Expected Disturbance Space (EDS) in steady-state operability reflects on uncertainties in model parameters. In panel stamping process, EDS reflects on natural uncertainty due to sensor noise and process disturbances, and model parameter uncertainty such as, variations in fixture and sensors position.

Mathematical formulation of EDS is the following:

$$EDS = \bigcup_{d \in EDS} DIS_u(d) \quad \text{(B.47)}$$

Thus in panel stamping process, expected disturbances $d$ in DIS are studied as a function of the variables identified with ACRONES, see Table B.4:

$$d = f\left(X_1 \pm 3\sigma, X_2 \pm 3\sigma \;\; P_{i_{x,z}} \pm \Delta X_1, M_{i_{x,z}} \pm \Delta X_2\right) \tag{B.48}$$

Mathematical formulation of EDS in the panel stamping process is the following:

$$EDS = \bigcup_{d \in EDS} DIS_u\left(X_1 \pm 3\sigma, X_2 \pm 3\sigma \;\; P_{i_{x,z}} \pm \Delta X_1, M_{i_{x,z}} \pm \Delta X_2\right) \tag{B.49}$$

## cDSP Construct for the Steady-State Operability Analysis of a Panel Stamping Process

**Given**

*Design Parameters:*

| | | | |
|---|---|---|---|
| Number of stations | $N$ | 3 | [-] |
| Number of parts | $n_p$ | 4 | [-] |
| Potential fixture faults | $m_r$ | 18 | [-] |
| Degrees of freedom of 2-D rigid part | DOF | 3 | [-] |
| Desired process diagnosability index | $\mu_D$ | 100 | [%] |
| Desired process controllability index | $\mu_C$ | 100 | [%] |

*Operability Spaces:*

| | | | |
|---|---|---|---|
| Available Input Space | $AIS$ | $[-]$ | Table B.2 |
| Desired Output Space | $DOS$ | $[-]$ | Table B.3 |
| Expected Disturbance Space | $EDA$ | $[-]$ | Table B.4 |

*Design Alternatives:*

| | |
|---|---|
| 3- stage process with end-of-line sensing | Figure 5, a |
| 3- stage process with distributed sensing | Figure 5, b |
| 4- stage process with end-of-line sensing | Figure 6, a |
| 4- stage process with distributed sensing | Figure 6, b |

*Assumptions:*

Workpieces are 2-D rigid parts
There is only potential fixture faults in the process
Local directions of fixture points in x- direction are adjustable in n-stations
Sensors in x – and z – direction are positioned in the corner points
No three sensors are collinear in x- and z- direction
Fixture points $P_1$, $P_2$, $P_3$, $P_4$, $P_7$, $P_8$ are collinear in z- direction
Fixture points $P_5$, $P_6$ are collinear in z- direction
Process diagnosability is full
Process controllability is full
System goals weight coefficients are based on a designer decision
Operability spaces information are obtained from ACRONES

**Find**

*System Variables:*

| | | |
|---|---|---|
| Achievable Output Space | $AOS$ | $AOS \subset AIS$ |

| | | | | |
|---|---|---|---|---|
| Desirable Input Space | $DIS_d(y^N)$ | $DIS \subset DOS$ | | |
| Total Desirable Input Space | $DIS$ | $DIS = \bigcup_{y \in DOS} DIS_d(y) = \bigcup_{d \in EDS} DIS_y(d)$ | | |
| Tolerable Disturbance Space | $TDS$ | $TDS = \bigcup_{d \in TDS} AIS_u(d)$ | | |
| *Deviation Variables:* | | | | |
| Under achievement of the Goal 1 | | $d_1^-$ | | [-] |
| Under achievement of the Goal 2 | | $d_2^-$ | | [-] |
| Under achievement of the Goal 3 | | $d_3^-$ | | [-] |
| **Satisfy** | | | | |
| *System Constraints:* | | | | |
| Fixture points $P_i$ and $P_j$ cannot be the same points (i, j =1,…, 8) | $P_{i,j}$ | $P_{i,x} \neq P_{j,x}$<br>$P_{i,z} \neq P_{j,z}$ | $C_1$ | [mm] |
| Sensors points $M_i$ and $M_j$ cannot be the same points (i, j =1,…, 20) | $M_{i,j}$ | $M_{i,x} \neq M_{j,x}$<br>$M_{i,z} \neq M_{j,z}$ | $C_2$ | [mm] |
| Sensors have to take corner positions | $M_i$ | $M_{i,x} \equiv \min \vee \max$<br>$M_{i,z} \equiv \min \vee \max$ | $C_3$ | [mm] |
| No three sensors can be collinear in x- and z- direction | $M_{i,j,r}$ | $M_{i,x} \neq M_{j,x} \neq M_{r,x}$<br>$M_{i,z} \neq M_{j,z} \neq M_{r,z}$ | $C_4$ | [mm] |
| Fixture points $P_1$, $P_2$, $P_3$, $P_4$, $P_7$, $P_8$ must be collinear in z- direction | $P_{i,z}$ | $P_{1,z} = P_{2,z} = P_{3,z}$<br>$= P_{4,z} = P_{7,z}$<br>$= P_{8,z}$ | $C_5$ | [mm] |
| Fixture points $P_5$, $P_6$ must be collinear in z- direction | $P_{i,z}$ | $P_{5,z} = P_{6,z}$ | $C_6$ | [mm] |
| Product of deviation variables has to be equal to zero | $d_i^-, d_i^+$ | $d_i^- \times d_i^+ = 0$ | $C_7$ | [-] |
| Deviation variables have to be positive | $d_i^-, d_i^+$ | $d_i^-, d_i^+ \geq 0$ | $C_8$ | [-] |
| *System Goals:* | | | | |
| Maximize Servo Operability in the Output Space* | $\frac{\mu[AOS_u(d^N) \cap DOS]}{\mu[DOS]} + d_1^- - d_1^+ = 1$ | | $G_1$ | [-] |
| Maximize Servo Operability Index in the Input Space** | $\frac{\mu[AIS \cap DIS_y(d^N)]}{\mu[DIS_y(d^N)]} + d_1^- - d_1^+ = 1$ | | $G_1$ | [-] |
| Maximize Regulatory Operability Index* | $\frac{\mu[TDS \cap EDS]}{\mu[EDS]} + d_2^- - d_2^+ = 1$ | | $G_2$ | [-] |
| Maximize Regulatory Operability** | $\frac{\mu[AIS \cap DIS_d(y^N)]}{\mu[DIS_d(y^N)]} + d_2^- - d_2^+ = 1$ | | $G_2$ | [-] |
| Maximize System Operability | $\frac{\mu[AIS \cap DIS]}{\mu[DIS]} + d_3^- - d_3^+ = 1$ | | $G_3$ | [-] |
| *System Bounds:* | | | | |
| Total number of sensors | $M_i$ | 0 – 20 | $B_1$ | [-] |
| Distribution of sensors per station | $M_{i,k}$ | 0 – 8 | $B_2$ | [-] |
| Total number of sensing stations | $M_{Si}$ | 0 – n | $B_3$ | [-] |
| Dimensional variations at station | $y_k$ | -0.8 – 0.8 | $B_4$ | [mm] |
| Overall cost | Cost | 0 – n | $B_5$ | [$] |

| | | | | |
|---|---|---|---|---|
| Servo Operability Index in the Output Space or Servo Operability in the Input Space | $SOIOS\ or\ SOIIS$ | 0 – 100 | $B_6$ | [%] |
| Regulatory Operability Index | $ROI$ | 0 – 100 | $B_7$ | [%] |
| Operability Index | $OI$ | 0 – 100 | $B_8$ | [%] |
| **Minimize** | | | | |
| *Deviation Functions:* | | | | |
| Preemptive formulation where we are minimizing the goal function | | $Z = \min(d_i^-)$ | | [-] |

# Appendix C. Continuously Stirred Tank Reactors (CSTR) Process Description

In Appendix C main equations describing cSTR process and operability and disturbance spaces parameters, Tables C1 – C4, are presented. Design procedure and alternatives for a single- and double-cSTR, Tables C5 – C8, are presented. Lastly, the cDSP construct for the Steady-State Operability Analysis of cSTR, and Minimum-Time Optimal Control Problem is presented.

### Main cSTR Process Equations

Mass balances and energy balances for both single-reactor and reactors-in-series systems:

$$\frac{dV_i}{dt} = F_{i-1} - F_i \tag{C.1}$$

$$\frac{d(V_i C_{Ai})}{dt} = F_{i-1} C_{Ai-1} - F_i C_{Ai} - V_i k_i C_{Ai} \tag{C.2}$$

$$\rho c_p \frac{d(V_i T_i)}{dt} = \rho c_p F_{i-1} T_{i-1} - \rho c_p F_i T_i + (-\Delta H) V_i k_i C_{Ai} - U A_i (T_i - T_{Ci}) \tag{C.3}$$

$$\rho_C c_{pC} V_{Ci} \frac{dT_{Ci}}{dt} = \rho_C c_{pC} F_{Ci} (T_{C0} - T_{Ci}) + U A_i (T_i - T_{Ci}) \tag{C.4}$$

Parameters calculation:

$$k_i = k_0 e^{-E/RT_i} \tag{C.5}$$

$$A_i = A_{si} + A_{bi} \tag{C.6}$$

$$A_{si} = A_{si}^R \frac{V_i}{V_i^R} \tag{C.7}$$

State variable transformation:

$$x_{1i} = \frac{V_i}{V_i^R} \tag{C.8}$$

$$x_{2i} = \frac{C_{Ai}}{C_A^R} \tag{C.9}$$

$$x_{3i} = \frac{T_i - T^R}{T^R} \tag{C.10}$$

$$x_{4i} = \frac{T_{Ci} - T^R}{T^R} \tag{C.11}$$

$$q_i = \frac{F_i}{F^R} \tag{C.12}$$

$$q_{Ci} = \frac{F_{Ci}}{F_{Ci}^R} \tag{C.13}$$

$$\alpha_i = \frac{F_{Ci}^R}{F^R} \tag{C.14}$$

$$\tau = \frac{tF^R}{V^R} \tag{C.15}$$

$$\phi_i = \frac{k_0 e^{-\Upsilon} V_i^R}{F^R} \tag{C.16}$$

$$\Upsilon = \frac{E}{RT^R} \tag{C.17}$$

$$\mu_i = \frac{V_i}{V_{Ci}} \tag{C.18}$$

$$\upsilon_i = \frac{V_1^R}{V_i^R} \tag{C.19}$$

$$\beta = \frac{(-\Delta H) C_A^R}{\rho c_p T^R} \tag{C.20}$$

$$\xi = \frac{\rho c_p}{\rho c_{pc}} \tag{C.21}$$

$$\delta_{si} = \frac{UA_{si}^R}{\rho c_p F^R} \tag{C.22}$$

$$\delta_{bi} = \frac{UA_{bi}}{\rho c_p F^R} \tag{C.23}$$

$$f(x_{3i}) = exp\left(\frac{\Upsilon x_{3i}}{1 + x_{3i}}\right) \tag{C.24}$$

Transformed state equations:

$$\frac{dx_{1i}}{d\tau} = \upsilon_i(q_{i-1} - q_i) \tag{C.25}$$

$$\frac{dx_{2i}}{d\tau} = \frac{\upsilon_i}{x_{1i}}[q_{i-1}(x_{2i-1} - x_{2i}) - \phi_i f(x_{3i})x_{1i}x_{2i}] \tag{C.26}$$

$$\frac{dx_{3i}}{d\tau} = \frac{\upsilon_i}{x_{1i}}[q_{i-1}(x_{3i-1} - x_{3i}) + \beta\phi_i f(x_{3i})x_{1i}x_{2i} - (\delta_{si}x_{1i} + \delta_{bi})(x_{3i} - x_{4i})] \tag{C.27}$$

$$\frac{dx_{4i}}{d\tau} = \upsilon_i[\alpha_i\mu_i q_{Ci}(x_{4i-1} - x_{4i}) + \xi\mu_i f(x_{3i})x_{1i}x_{2i} - (\delta_{si}x_{1i} + \delta_{bi})(x_{3i} - x_{4i})] \tag{C.28}$$

**Table C.1. cSTR Design Parameters**

| Parameter | Value | Units |
|---|---|---|
| $E$ | 30000 | [Btu lbmol$^{-1}$] |
| $k_{140°\text{F}}$ | 0.5 | [h$^{-1}$] |
| $C_{A0}$ | 1.0 | [lbmol ft$^{-3}$] |
| $U$ | 300 | [Btu h$^{-1}$°F$^{-1}$ft$^{-2}$] |
| $T_0$ | 70 | [°F] |
| $T_{C0}$ | 70 | [°F] |
| $\Delta H$ | -30000 | [Btu lbmol$^{-1}$] |
| $c_p$ | 0.75 | [Btu lb$^{-1}$°F$^{-1}$] |
| $c_{pc}$ | 1.00 | [Btu lb$^{-1}$°F$^{-1}$] |
| $M$ | 50.0 | [lb lbmol$^{-1}$] |
| $\rho$ | 50.0 | [lb ft$^{-3}$] |
| $\rho_c$ | 62.3 | [lb ft$^{-3}$] |

**Table C.2. Available Input Space (AIS)**

| Symbol | Description | Lower Bound | Upper Bound | Units |
|---|---|---|---|---|
| $F_{Ci}$ | coolant flow rate | 0 | $4F_{Ci}^{R}$ | [$ft^3h^{-1}$] |
| $F_i$ | product flow rate | 50 | 150 | [$ft^3h^{-1}$] |
| $V_i$ | volume of the reaction mixture | $0.3V^R$ODF | $V^R$ODF | [$ft^3$] |

**Table C.3. Desired Output Space (DOS)**

| Symbol | Description | Lower Bound | Upper Bound | Units |
|---|---|---|---|---|
| $C_{Ai}$ | exit of concentration of reactor A | 0.02 | 0.2 | [lbmol $ft^3$] |
| $T_i$ | reactor temperature | 100 | 200 | [°F] |

**Table C.4. Expected Disturbance Space (EDS)**

| Symbol | Description | Lower Bound | Upper Bound | Units |
|---|---|---|---|---|
| $T_{i-1}$ | feed temperature | 50 | 90 | [°F] |
| $F_{i-1}$ | feed flow rate | 50 | 150 | [$ft^3h^{-1}$] |

Assumptions:

- Rate of close and opening of valves of A: $\left[\frac{dF_i}{dt}\right] \leq 19250$ [$ft^3h^{-2}$],
- Rate of close and opening of valves at coolant: $\left[\frac{dF_{Ci}}{dt}\right] \leq 19250$ [$ft^3h^{-2}$],
- Constant physical properties,
- Complete mixing.

### Design Procedure and Alternatives for a single-cSTR

**Table C.5. Design Specifications**

| Symbol | Description | Equation | Assumptions |
|---|---|---|---|
| $F_{i-1}$ | feed flow rate | | |
| $C_{Ai-1}$ | feed concentration of A | | |
| $x$ | conversion | | |
| $C_{Ai}$ | reactor exit concentration | $C_{Ai} = C_{Ai-1}(1-x)$ | |
| $V_i$ | reactor volume | $V_i = \frac{F_{i-1}(C_{Ai-1} - C_{Ai})}{kC_{Ai}}$ | height to diameter ratio of 2 |
| $V_{Ci}$ | volume of the jacket | | thickness of 4 inches |
| $F_{Ci}$ | coolant flow rate | from Equation B.4 | |
| $T_{Ci}$ | jacket temperature | from Equation B.3 | |

**Table C.6. Design Alternatives for Single-cSTR**

| | D1 | D2 | D3 |
|---|---|---|---|
| $T$ | 140.00 | 160.00 | 180.00 |
| $V^R$ | 3800.00 | 1689.61 | 790.29 |
| $Q^R$ | 2587.50 | 2512.50 | 2437.50 |
| ${F_c}^R$ | 81.90 | 63.88 | 53.12 |
| $\Delta T$ | 6.77 | 11.29 | 18.17 |

## Design Procedure and Alternatives for Double-cSTR

**Table C.7. Design Specifications**

| Symbol | Description | Equation | Assumptions |
|---|---|---|---|
| $F_0$ | feed flow rate | | |
| $C_{A0}$ | concentration of component A in the 2nd reactor | | |
| $x$ | exit concentration | | |
| $C_{A2}$ | reactor exit concentration in the 2nd reactor | $C_{A2} = C_{A0}(1-x)$ | |
| $C_{A1}$ | steady-state material balance of the 1st reactor | $C_{A1} = \frac{F_0 C_{A0}}{F_0 + F_1 k_1}$ | |
| $V_2$ | steady-state material balance of the 2nd reactor | $V_2 = \frac{F_0(C_{A1} - C_{A2})}{k_2 C_{A2}}$ | $V_2 = R_V V_1$ |
| $V_1$ | volume of the 1st reactor | $R_V k_1 k_2 (1-x) V_1^2 + F_0(1-x)(k_1 + R_V k_2) V_1 - F_0^2 x = 0$ | |
| $C_{A1}$ | reactor exit concentration in the 1st reactor | $C_{A1} = \frac{(V_2 k_2 + F_0)}{F_0} C_{A2}$ | |
| $V_{Ci}$ | volume of the jacket | | |
| $F_{Ci}$ | coolant flow rate | from Equation B.4 | |
| $T_{Ci}$ | jacket temperature | from Equation B.3 | |

**Table C.8, a). Design Alternatives for Two-CSTR for Rv=1.0**

| Variables | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 |
|---|---|---|---|---|---|---|---|---|---|
| $T_1$ | 140.00 | 140.00 | 140.00 | 160.0 | 160.0 | 160.0 | 180.0 | 180.0 | 180.0 |
| $T_1$ | 140.00 | 160.00 | 180.00 | 140.00 | 160.00 | 180.00 | 140.00 | 160.00 | 180.00 |
| ${V_1}^R$ | 694.43 | 454.53 | 294.72 | 454.53 | 308.77 | 207.75 | 294.72 | 207.75 | 144.42 |
| ${V_2}^R$ | 694.43 | 454.53 | 294.72 | 454.53 | 308.77 | 207.75 | 294.72 | 207.75 | 144.42 |
| ${C_{A1}}^R$ | 0.22 | 0.31 | 0.40 | 0.16 | 0.22 | 0.30 | 0.12 | 0.17 | 0.22 |
| ${Q_1}^R$ | 2066.68 | 1820.81 | 1524.68 | 2171.60 | 1991.69 | 1763.28 | 2216.46 | 2087.06 | 1916.68 |
| ${Q_2}^R$ | 520.82 | 691.69 | 912.82 | 415.90 | 520.82 | 674.22 | 371.04 | 425.44 | 520.82 |
| ${F_{c1}}^R$ | 77.73 | 72.34 | 63.49 | 65.26 | 64.06 | 60.87 | 56.79 | 57.94 | 58.44 |
| ${F_{c2}}^R$ | 15.85 | 16.77 | 18.86 | 12.70 | 12.60 | 13.80 | 11.48 | 10.35 | 10.64 |
| $\Delta T_1$ | 16.79 | 19.63 | 21.94 | 23.41 | 27.78 | 32.03 | 31.89 | 37.91 | 44.37 |
| $\Delta T_2$ | 4.23 | 7.46 | 13.13 | 4.48 | 7.26 | 12.25 | 5.34 | 7.73 | 12.06 |

**Table C.8, b). Design Alternatives for Two-CSTR for Rv=2.0**

| Variables | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 |
|---|---|---|---|---|---|---|---|---|---|
| $T_1$ | 140.00 | 140.00 | 140.00 | 160.0 | 160.0 | 160.0 | 180.0 | 180.0 | 180.0 |
| $T_1$ | 140.00 | 160.00 | 180.00 | 140.00 | 160.00 | 180.00 | 140.00 | 160.00 | 180.00 |
| ${V_1}^R$ | 484.43 | 306.61 | 191.62 | 327.30 | 215.39 | 140.46 | 219.10 | 149.30 | 100.75 |
| ${V_2}^R$ | 968.86 | 613.21 | 383.25 | 654.60 | 430.79 | 280.91 | 438.20 | 298.60 | 201.50 |
| ${C_{A1}}^R$ | 0.29 | 0.39 | 0.51 | 0.21 | 0.29 | 0.39 | 0.16 | 0.22 | 0.29 |
| ${Q_1}^R$ | 1860.86 | 1553.15 | 1205.42 | 2021.55 | 1785.86 | 1499.46 | 2108.85 | 1933.83 | 1710.86 |
| ${Q_2}^R$ | 726.64 | 959.35 | 1232.08 | 565.95 | 726.64 | 938.04 | 478.65 | 578.67 | 726.64 |
| ${F_{c1}}^R$ | 73.34 | 64.44 | 51.45 | 64.34 | 61.27 | 54.92 | 57.79 | 58.45 | 57.40 |
| ${F_{c2}}^R$ | 22.29 | 23.55 | 26.92 | 17.37 | 17.76 | 19.54 | 14.80 | 14.17 | 15.06 |
| $\Delta T_1$ | 19.22 | 21.77 | 23.11 | 27.12 | 31.67 | 35.36 | 36.97 | 43.79 | 50.35 |
| $\Delta T_2$ | 4.73 | 8.47 | 14.88 | 4.78 | 8.12 | 13.94 | 5.29 | 8.25 | 13.47 |

**Table C.8, c). Design Alternatives for Two-CSTR for Rv=0.5**

| Variables | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 |
|---|---|---|---|---|---|---|---|---|---|
| $T_1$ | 140.00 | 140.00 | 140.00 | 160.0 | 160.0 | 160.0 | 180.0 | 180.0 | 180.0 |
| $T_1$ | 140.00 | 160.00 | 180.00 | 140.00 | 160.00 | 180.00 | 140.00 | 160.00 | 180.00 |
| ${V_1}^R$ | 968.86 | 654.60 | 438.20 | 613.21 | 430.79 | 298.00 | 383.25 | 280.91 | 201.50 |
| ${V_2}^R$ | 484.43 | 327.30 | 219.10 | 306.61 | 215.39 | 149.30 | 191.62 | 140.46 | 100.75 |
| ${C_{A1}}^R$ | 0.17 | 0.23 | 0.31 | 0.13 | 0.17 | 0.23 | 0.10 | 0.13 | 0.17 |
| ${Q_1}^R$ | 2224.18 | 2035.42 | 1797.36 | 2282.55 | 2149.18 | 1974.08 | 2293.78 | 2200.58 | 2074.18 |
| ${Q_2}^R$ | 363.32 | 477.08 | 640.14 | 304.95 | 363.32 | 463.42 | 293.72 | 311.92 | 363.32 |
| ${F_{c1}}^R$ | 80.16 | 77.15 | 71.73 | 65.40 | 65.18 | 63.88 | 55.78 | 56.97 | 58.02 |
| ${F_{c2}}^R$ | 10.98 | 11.42 | 12.97 | 9.29 | 8.70 | 9.32 | 9.13 | 7.55 | 7.32 |
| $\Delta T_1$ | 14.48 | 17.20 | 19.85 | 20.15 | 24.01 | 28.16 | 27.70 | 32.69 | 38.46 |
| $\Delta T_2$ | 3.75 | 6.40 | 11.22 | 4.27 | 6.44 | 10.49 | 5.63 | 7.36 | 10.69 |

For more information about the CSTR model see Subramanian and co-authors (Subramanian, et al., 2001).

## cDSP Construct for the Steady-State Operability Analysis of cSTR

**Given**

*Design Parameters:*

| | | | | |
|---|---|---|---|---|
| Activation energy | $E$ | 30000 | [Btu lbmol$^{-1}$] | Table C.1 |
| Reaction rate constant | $k_{140°F}$ | 0.5 | [h$^{-1}$] | Table C.1 |
| Feed concentration of A | $C_{A0}$ | 1.0 | [lbmol ft$^{-3}$] | Table C.1 |
| Overall heat-transfer coefficient | $U$ | 300 | [Btu h$^{-1}$°F$^{-1}$ft$^{-2}$] | Table C.1 |
| Feed temperature | $T_0$ | 70 | [°F] | Table C.1 |
| Coolant feed temperature | $T_{C0}$ | 70 | [°F] | Table C.1 |
| Heat of reaction | $\Delta H$ | -30000 | [Btu lbmol$^{-1}$] | Table C.1 |
| Heat capacity of A | $c_p$ | 0.75 | [Btu lb$^{-1}$°F$^{-1}$] | Table C.1 |
| Heat capacity of coolant | $c_{pc}$ | 1.00 | [Btu lb$^{-1}$°F$^{-1}$] | Table C.1 |

| | | | | |
|---|---|---|---|---|
| Molecular weight of A | $M$ | 50.0 | $[\mathrm{lb\ lbmol^{-1}}]$ | Table C.1 |
| Density of A | $\rho$ | 50.0 | $[\mathrm{lb\ ft^{-3}}]$ | Table C.1 |
| Density of coolant | $\rho_c$ | 62.3 | $[\mathrm{lb\ ft^{-3}}]$ | Table C.1 |
| *Operability Spaces:* | | | | |
| Desired Output Space | $DOS$ | | $[-]$ | Table C.3 |
| Expected Disturbance Space | $EDA$ | | $[-]$ | Table C.4 |
| Available Input Space | $AIS$ | | $[-]$ | Table C.2 |
| *Design Alternatives:* | | | | |
| Single CSTR | | | | Figure 3.3, a |
| Double CSTR | | | | Figure 3.3, b |
| Reactor temperature | $T_i$ | 140 | [°F] | Table C.5 |
| Reactor temperature | $T_i$ | 160 | [°F] | Table C.5 |
| Reactor temperature | $T_i$ | 180 | [°F] | Table C.5 |
| Volume ratio | $R_V$ | 0.5÷2.0 | [-] | |
| *Assumptions:* | | | | |
| Rate of close and opening of valves at A | $\frac{dF_i}{dt}$ | 19250 | $[\mathrm{ft^3 h^{-2}}]$ | |
| Rate of close and opening of valves at coolant | $\frac{dF_{Ci}}{dt}$ | 19250 | $[\mathrm{ft^3 h^{-2}}]$ | |
| Height to diameter ratio of reactor volume | $\frac{h_i}{d_i}$ | 2 | $[-]$ | Table C.4 |
| Volume of the jacket thickness | $w_{Ci}$ | 4 | [in] | Table C.4 |
| Volume of the 2nd reactor | $V_2$ | | | Table C.7 |

**Find**

*System Variables:*

| | | |
|---|---|---|
| Achievable Output Space | $AOS$ | $AOS \subset AIS$ |
| Available Input Space | $AIS$ | Table B.1 |
| Desirable Input Space | $DIS_d(y^N)$ | $DIS \subset DOS$ |
| Total Desirable Input Space | $DIS$ | $DIS = \bigcup_{y \in DOS} DIS_d(y) = \bigcup_{d \in EDS} DIS_y(d)$ |
| Tolerable Disturbance Space | $TDS$ | |
| Max allowable performance time | $t_f^d$ | $t_f^d(y_{sp}, d)$ |
| Max time for system to achieve stability | $t_f^*$ | $t_f^*(y_{sp}, d)$ |
| Dynamic Desired Available Operability Spaces | $DDAOS$ | $DDAOS = DDOS \cap DAOS$ |
| Dynamic Desired Expected Deviation Space | $DDEDS$ | $DDEDS = DOS \cup EDS$ |

*Deviation Variables:*

| | | |
|---|---|---|
| Under achievement of the Goal 1 | $d_1^-$ | [-] |
| Under achievement of the Goal 2 | $d_2^-$ | [-] |
| Under achievement of the Goal 3 | $d_3^-$ | [-] |
| Under achievement of the Goal 4 | $d_4^-$ | [-] |

**Satisfy**

*System Constraints:*

| | | | | |
|---|---|---|---|---|
| Response time has to be less than or equal to the desired response time | | $t_f \le t_f^d$ | $C_1$ | [s] |
| Response time has to be greater than or equal to time for system to achieve stability | | $t_f \ge t_f^*$ | $C_2$ | [s] |
| Product of deviation variables has to be equal to zero | $d_i^-, d_i^+$ | $d_i^- \times d_i^+ = 0$ | $C_1$ | [-] |
| Deviation variables have to be positive | $d_i^-, d_i^+$ | $d_i^-, d_i^+ \ge 0$ | $C_2$ | [-] |

| | | | | |
|---|---|---|---|---|
| *System Goals:* | | | | |
| Maximize Servo Operability in the Output Space* | $\frac{\mu[AOS_u(d^N) \cap DOS]}{\mu[DOS]} + d_1^- - d_1^+ = 1$ | | G1 | [-] |
| Maximize Servo Operability in the Input Space** | $\frac{\mu[AIS \cap DIS_y(d^N)]}{\mu[DIS_y(d^N)]} + d_1^- - d_1^+ = 1$ | | G1 | [-] |
| Maximize Regulatory Operability* | $\frac{\mu[TDS \cap EDS]}{\mu[EDS]} + d_2^- - d_2^+ = 1$ | | G2 | [-] |
| Maximize Regulatory Operability** | $\frac{\mu[AIS \cap DIS_d(y^N)]}{\mu[DIS_d(y^N)]} + d_2^- - d_2^+ = 1$ | | G2 | [-] |
| Maximize System Operability | $\frac{\mu[AIS \cap DIS]}{\mu[DIS]} + d_3^- - d_3^+ = 1$ | | G3 | [-] |
| Maximize Dynamic Operability Index | $\frac{\mu[DOS \cup EDS]}{\mu[DDOS \cap DAOS]} + d_4^- - d_4^+ = 1$ | | G4 | [-] |
| *System Bounds:* | | | | |
| Coolant flow rate | $F_{Ci}$ | 0 - $4F_{Ci}^R$ | B1 | [$ft^3 h^{-1}$] |
| Product flow rate | $F_i$ | 50 - 150 | B2 | [$ft^3 h^{-1}$] |
| Volume of the reaction mixture | $V_i$ | $0.3V^R$ - $V^R$ | B3 | [$ft^3$] |
| Exit of concentration of reactor A | $C_{Ai}$ | 0.02 – 0.2 | | [lbmol $ft^3$] |
| Reactor temperature | $T_i$ | 100 – 200 | B4 | [°F] |
| Feed temperature | $T_{i-1}$ | 50 – 90 | B5 | [°F] |
| Feed flow rate | $F_{i-1}$ | 50 – 150 | B6 | [$ft^3 h^{-1}$] |
| Servo Operability Index in the Output Space | $SOIOS$ | 0 – 100 | B7 | [%] |
| Regulatory Operability Index | $ROI$ | 0 – 100 | B8 | [%] |
| Operability Index | $OI$ | 0 – 100 | B9 | [%] |
| Systems response time | $t_f$ | 0 - n | B10 | [s] |
| Time for system to achieve stability | $t_f^*$ | min-time optimal control - ∞ | B11 | [s] |
| **Minimize** | | | | |
| *Deviation Functions:* | | | | |
| Preemptive formulation where we are minimizing the goal function | | $Z = \min(d_i^-)$ | | [-] |

* Variant system design

** Original system design

## Minimum-Time Optimal Control Problem

$$t_f^*(y_{sp}, d) = \min_u \int_0^{t_f} dt \tag{C.29}$$

Subjected to:

$$\dot{x} = f(x, u, d); x(0) = x_0$$

$$y = g(x, u, d)$$

$$h_1(y, \dot{x}, x, \dot{u}, u, d) = 0$$

$$h_2(y, \dot{x}, x, \dot{u}, u, d) \leq 0$$

$x_0, y_{sp}, d$ given

such that:

$$\dot{x}_1 = \frac{0.3}{F^R}(x_1 - x_2)$$

$$\dot{x}_2 = \frac{0.3V^R}{x_3}\left[\frac{x_1}{F^R C_A^R}(C_{A0} - x_4) - \frac{0.5x_3x_4}{F^R C_A^R} e^{\left[\frac{E}{x_5 R T^R}(x_5 - T^R)\right]}\right]$$

$$\dot{x}_3 = \frac{0.3V^R}{x_3}\left[\frac{x_1}{T^R F^R}(T_0 - x_5) + \frac{(-\Delta H)k_0 x_3 x_4}{\rho c_p T^R F^R} e^{\left(\frac{x_5 - T^R}{x_5}\right)}\right.$$

$$\left. - \frac{U}{\rho c_p T^R F^R}\left(A_s^R \frac{x_3}{V^R} + A_b\right)(x_5 - x_7)\right]$$

$$\dot{x}_4 = \frac{0.3V^R}{x_3}\left[\frac{x_3 x_7}{T^R F^R V_C}(T_{C0} - x_7) + \frac{U x_3}{\rho c_{pc} T^R F^R V_C}\left(A_s^R \frac{x_3}{V^R} + A_b\right)(x_5 - x_7)\right]$$