Complexity Thinking and Cyber-Physical Systems

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Abstract — *Cyber-physical systems are currently seen as a panacea to global competitiveness in developed economies. This work formulates the concept of complexity thinking and discusses practical implication of complexity in cyber-physical systems. Avoidance, prevention and reduction are the existing strategies for managing complexity in production. There is lack of clear consensus in literature and practice with regards to definition, modeling and measurement of complexity in production. In addition to the prevailing confusion related to the types of complexity, there is an acute scarcity of methods to empirically measure production complexity. The following work analyzes the existing complexity management literature and provides a framework to manage production complexity. For further use to the industry partners, the importance of complexity management in extending the lean management framework is discussed.*

Keywords—complexity in production, lean management, cyber-physical systems, System performance, industry interactions

I. Introduction

The constant endeavour to be globally competitive [1] requires efficient and flexible sub-systems that can handle the variety and dynamic interchanging relationships of the system elements. The complexities involved in producing an increasingly high variety of products to satisfy dynamic customer demand is a challenge from an economic, social policy and environmental perspective.

Shorter product and technology lifecycles, changing legal regulations and globalized supply chains [1], [2], [3] have resulted in customer specific production configurations and decentralized networks, adding more complexity [4]. In 2004, it was estimated that in total 75% of the EU GDP and 70% of employment in Europe were related to manufacturing [5].

Although the lines of products and services are blurring, the manufacturing industry today is witnessing a renaissance especially in Europe [6].

Achieving continuous operational excellence in global and local value chains depends upon continuous innovation in products and processes. The emergence of cyber-physical systems [6], [7], [8] has triggered a paradigm change in industrial automation.

Automated systems and the increasing focus on automation [9] in industry are seen as one of the solutions to be flexible and globally competitive. The effects of increasing automation on job simplification for the operator are debatable and yet to be agreed upon empirically. But certainly, increasing automation at the workplace shifts system complexity towards support personal and system designers.

Complexity management is not only dealing with increasing variety in production, as commonly misunderstood. However, there has been scant focus on organizational [10] and supply chain drivers [11] affecting process complexity [2]. The paper aims to motivate complexity based thinking in production and underline the importance of system thinking to deal with the increasing levels of automation.

II. OVERVIEW

In the following section, we discuss relevant existing concepts and studies forming the basis for complexity model development. We define cyber-physical systems (CPS) [12] and cyber-physical production systems (CPPS) [13]. Furthermore, the importance of determining the appropriate automation and complexity levels will be discussed.

A. Cyber Physical Systems

Cyber-physical systems (CPS) are integrations of computation with physical processes [12]. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa." [13].

CPS as a concept has been investigated in different industry contexts; smart grid [14], virtual production [15] to name a few which underlines the need for integrated studies[16] and a concurrent approach from production, information technology and electronics industries for effective implementation of CPS.

Cyber-physical systems in production CPPS [13] are defined as tailor-made (customized) sub-systems which automatize the configuration of the system, in order to have a flexible, agile and efficient production. CPPS are designed to break open the classic automation pyramid and replace it with networked, decentralized or partly self-organizing services.

Usage of "Transport bugs" [9] in warehouse logistics is an example of CPPS and of the resulting increased sophistication in production systems. These "transport bugs" or self-driven goods transporters process information and operate in a decentralized mode.

Furthermore, they might choose their own operation configuration (e.g. forks or containers for transportation) and interact with each other to manage traffic flow. The entire material flow control is spread across a number of virtual shoulders. In case of disruption, the bugs react on their own and rectify the problem.

This system requires minimum human intervention but has to work amidst less sophisticated humans who already have to deal with an array of challenging and sometimes unpredictable problems. The increasing level of sophistication will drastically change the level of complexity for shop floor employees, e. g. machine operators and M&R (maintenance and repair) personnel.

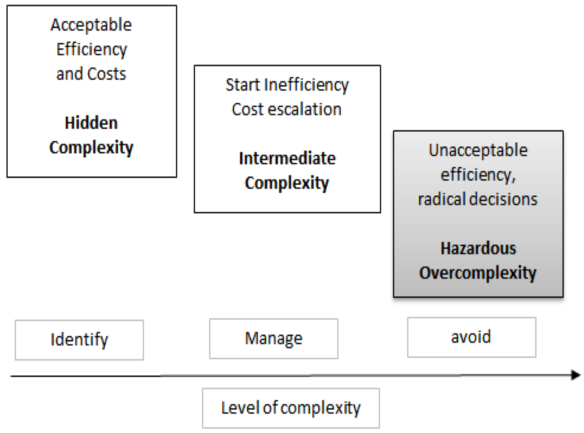
The existing skill sets of employees, existing management tools and methodologies might be inadequate to deal with the increasing system complexity.

B. Understanding Complexity

The studies of the Nobel Prize winner Prigogine [17], which looked at complexities in biological systems, invigorated research and renewed the focus to complexity studies. Complexity management researchers have stated that complexity can either be controlled or managed but not prevented [18].

Complexity management has origins [19] from systems theory, natural sciences, economics and business management.

The complexity management approach [20] builds upon a number of studies resulting in usage of confusing and intertwined terms such as chaotic systems, complex networks and complexity in a system. Complexity is structural property of a system



i.e. inherent property which persists in a system even in absence of external agents [21].

Figure 1 shows the common effects of inherent complexity on the system performance.

Fig 1: Motivation for complexity Studies

Low system performance becomes visible through changes in efficiency, costs and quality, finally resulting in panic and radical decisions. Managing system complexity helps in identifying hidden or unseen causes of system failure proactively giving hints on the possible areas of improvement, in order to avoid post analysis on system degradation.

~~**Fig 1: Motivation for complexity Studies**~~

A majority of the authors define and interpret complexity differently i.e. either as a mathematical function [22], [23], [24], subjective [25] and perceived [26] type to name a few. Furthermore the drivers of complexity are determined using a number of methodologies namely mathematical models [22], operations research models [23] or an indigenous case specific approach [24], [25], [27]. There is a gap and lack of consensus in literature for the interpretation, measurement and management of complexity in production. For a detailed study and summary of the widely used methodologies for measuring complexity, one can refer to [19], [21] and [28].

The complexity approach which is further discussed clears the confusion in conceptualizing complexity in production and makes it possible for the system manager to link the cause and effect in order to assess the system behavior as a whole and to investigate the drivers that influence system performance.

Before understanding the approach to measure complexity, the link between complexity and levels of automation needs to be investigated. Automation, among other measures, may lead to increase in productivity [29]. The economic benefit of automation is strong, but is not the only motivation for increasing the level of automation.

Satchell [30] defined automation as the replacement of human activity by machine activities. Parasuraman et.al. [31] presented a more complete definition of automation, "Automation refers to the full or partial replacement of a function previously carried out by the human operator."

Harlin [32] highlights the problem of realizing an appropriate level of automation [10]. It is desired that increases in levels of automation will be effective, but the actual state of system performance is different from the expected state due to a number of factors mainly related to complexity. The expected state is the situation where the full potential of automation is realized and its negative side effects are negligible.

Hence, complexity management will help in determining optimum automation levels which shall result in decreasing human workload, improving process accuracy and worker safety [31].

C. *Measuring Complexity in Production*

In literature, complexity is primarily modeled either through information diversity [22] or an entropy model [35] of the system. Following the analysis by Mattson [25], both the information diversity and entropy model approach, though complementary, are quite abstract, therefore difficult to understand and use in practice.

The mathematical models [22], [35] and [36] although rich in academic rigor, have their limitations. The methodologies used for development of these models are not congruent or rather too sophisticated for practical use on the shop floor.

Furthermore, empirical evidences and hints on implementing the model for the end user i.e. employees of the shop floor, are missing.

The conceptual models are case specific, for example complexity in software industry [37] or looking at managing complexity in production through one aspect of complexity usually variety reduction [27],[28], [35].

To summarize, the existing approaches, be it qualitative [25], [27], [28], [35] and quantitative [22], [23],[24] are not evaluated for industry readiness parameters[38], [39] which is important to establish trustworthiness, applicability and transferability of a research design.

Although, scholars have studied complexity in production as early as 1958 [40], but the fact remains, that system complexity is not exactly detectable, measurable and manageable in its full expression. Therefore a certain degree of openness and creative thinking is suggested when dealing with complexity in production.

III. KMP APPROACH TO COMPLEXITY

A. *Defining Complexity*

The KMP approach for defining complexity in modern production systems takes into account the existing theoretical and empirical approaches [19], [28], [33] and [34]. The KMP model states that the complexity of a system is determined by the following four dimensions i.e. variety, dynamics, interdependence and uncertainty (Figure 2).

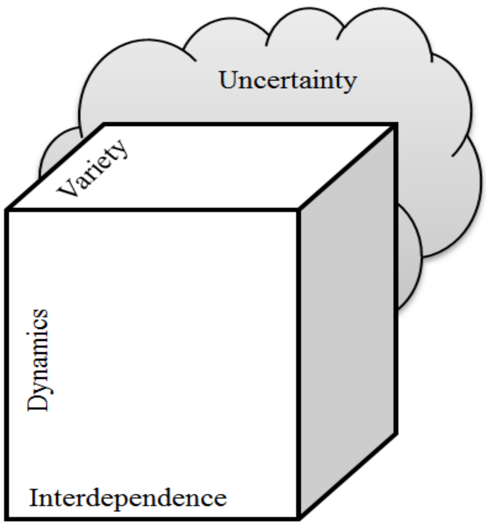


Fig 2: KMP Definition of Complexity

Variety includes the number of product and process variants. Interdependencies focus on the number and intensity of relations between different elements of a subsystem, influencing process design and system structure. Dynamics characterizes the temporal changes in the relationships of the elements. Uncertainty takes into account unknown influences or unpredictable external drivers, e.g. social or political events.

With respect to empirical measurement of complexity, the challenge lies in designing a holistic study which covers all the aspects of complexity and is easy to implement on the shop floor. The ease of implementation could be measured in terms of time and effort required in measurement of complexity.

Figure 3 gives an overview of the methodology for measuring complexity in production. The KMP complexity approach takes into account the subjective (intangible), objective (system performance numbers) and perceived views of the different stakeholders of the system. The total complexity of the system is analyzed using an indigenous approach to understand the system results and stakeholder mindset.

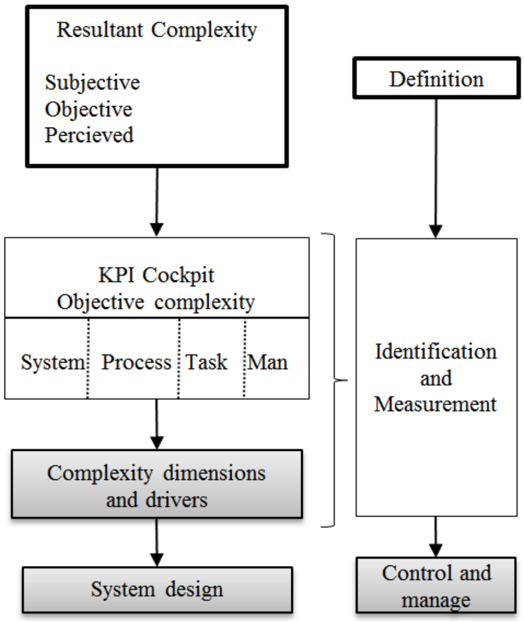


Fig 3: KMP Methodology to measure complexity

Using the ‘define, measure and manage’ framework [3], [41] along with our industry partners, we are currently developing a cockpit of key performance indicators (KPIs) which in part build on existing performance measures.

The KPIs not only look at standard performance measures, for example OEE [3] (overall equipment effectiveness), but also measure the integration time, the amount of mental load and physical load for new operators on the shop floor. Furthermore, relevant complexity drivers and causes for complexity in the process (rework), tasks (variety) and man (motivation) are being identified. These drivers will be measured, analyzed and correlated with the complexity dimensions and system performance.

The work is similar to [25] and [26] with respect to the analysis for the types of complexity, but differs on the identification and the holistic yet universally applicable approach for measuring complexity.

B. Complexity and Lean Production

Regardless of the cause, in practice significant complexity will exist, and how it is managed will be a key to be globally competitive.

Furthermore, complexity in production can serve as a key lever linking manufacturing strategy to organizational policies [10] and work allocation. Complexity management is different from lean management [41], [42] and other performance management [43] tools; it takes into account and encourages the congruence of all the system stakeholders.

The complexity approach urges the designer to be proactive and to identify hidden complexities in the system in order to avoid lack of control and the resulting need for ad-hoc decisions.

The KMP approach suggests that excessive complexity should be considered as a waste hindering value adding activity. As seen in Figure 4, lean production [41] and complexity management both aim towards improving system stability and performance. The advantages and methodology for lean production are known [41].

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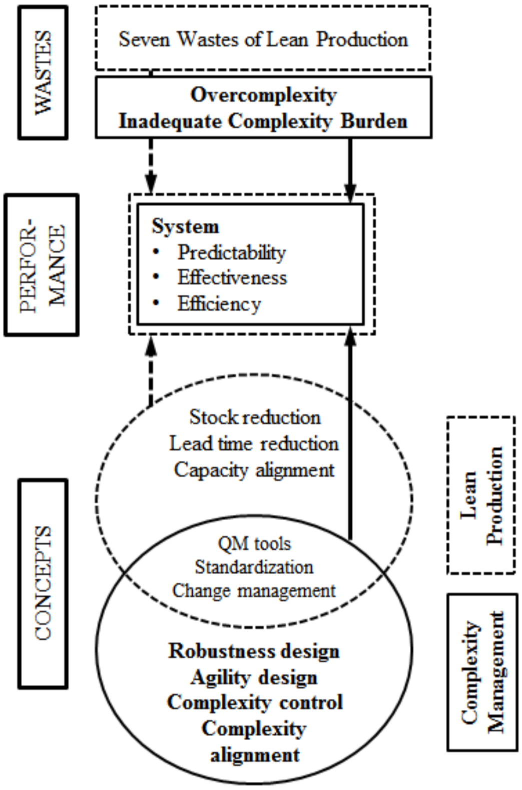

Fig 4: Same Goal, Different Approaches. Understanding Lean Production and Complexity Management

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There is an ongoing debate on the consequences of lean production. On one hand, lean production is believed to have negative consequences [15], [45] for the confidence of the employees and their job quality, on the other hand lean production is viewed as the means for achieving world-class performance in a humane way with positive effects on employees. Hence, depending on the implementer and the work environment, the effect of lean production on work characteristics and employee outcomes can be both positive and negative.

Complexity management in production extends the lean management framework in multiple ways. First, it views the process holistically from an employee, managerial and system perspective. Second, it identifies over-complexity and inadequate complexity as a complementary waste of production. Furthermore, it suggests usage of robustness and complexity design concepts to increase overall system performance.

Hence, complexity management in production helps in reducing the negative aspects of lean production and provides a new dimension to the system.

With the advent of CPPS, there would be increasingly complex and sophisticated man-machine interactions. Automatic acquisition, processing and mining of process data would change the quality control and waste reduction mechanisms in production systems.

IV. SUMMARY

The methodology presented in this paper is currently being tested and implemented on shop floors (high volume industrial production and automotive) with the help of objective analysis and subjective interviews. Furthermore, we have developed an assortment of key performances indicators to measure the three types of complexity which can be used to assess the system performance, process robustness and perceived complexity of the production employees.

The perceived complexity of the employees is to be measured through subjective interviews investigating the attitude of the operator towards changing workplace, increasing workload.

Using the actionable framework (seen in figure 3 and figure 4) a production manager can define and measure the complexity in production which can be a part of a continuous improvement exercise that simplifies or reduces the existing complexity in a system.

By stating over-complexity is a waste which needs to be managed, we extend the lean management framework. Our approach helps to look beyond the system results, thereby giving hints on the dimensions and drivers. This unique approach helps to proactively understand possible negative effects on the shop floor, limit the consequences of over complexity and redistribute complexity burden through task allocation, resulting in a robust and manageable system.

The transferability of academic studies into practice is valued through the effective use and implementation of industry academic interactions. Successful implementation of a complexity management approach requires active participation and congruence of top management, operators and their supervisors.

Future research will look at the sources, dimensions and drivers of complexity in different production industries in order to get interesting insights on the commonalities in the control and managing strategies for different manufacturing systems with varying complexity levels.

Further investigations will be made to measure changes in selected KPIs as a consequence of changes in complexity and system parameters in order to test and validate the hypotheses.

With the advent of increasing automation solutions in production [46] and the so called fourth industrial revolution, the existing gap between effect and levels of automation could be marginalized, but this will not be possible without managing the complexity levels of the system and the main driver, i.e. the human being.

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