Towards a Production Complexity Model that Supports Operation, Re-balancing and Man-hour Planning

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ABSTRACT

Mass customization and more variants, components, and frequent changes increase production complexity. This paper presents research project aimed at developing a feasible definition of complexity, a method for measuring complexity, which supports line rebalancing, man-hour planning, and complexity management, competence, and information support. The project is done in collaboration between Swerea IVF, Chalmers, Volvo Cars, Electrolux, Stoneridge, Electronics, and AB Volvo. Industrial studies were carried out to understand the needs for handling complexity. In parallel, a literature study was conducted over research on definitions, models and methods for complexity. In literature, complexity is commonly modelled by information and entropy of the system (randomness); and categorized into static/dynamic and subjective/objective. The research further concludes: unknown events increase with complexity, making management of uncertainty increasingly important, not only reducing but also coping with complexities; the role of humans and technology in work systems is crucial for coping with uncertainties; complexity models and methods must be easy to understand and use; and must take a holistic view of production; and include different user's perspective and the subjective complexity.

Keywords: manufacturing, complexity, entropy, information, indirect work, subjective, competence, operators, line balancing, man-hour planning

1 INTRODUCTION

Future production will be located in plants that flexibly and efficiently can produce new products, complying with environmental requirements. Demands from **mass customization and sustainable products** e.g. hybrid engines cause an increasingly complex production environment. Customization in this context refers to fabrication-to-order or assembly-to-order as modelled by Blecker et al. [1]. A common way to deal with mass customization and the flexibility that comes with such production is to use different forms of mix-model assembly systems.

A major contributor to the complexity is the **increasing number of components, variants, and changes**. For example, Volvo Cars Corporation anticipates the number of car components to increase by 50% to 100% within the next three years; the variants to be more differentiated e.g. fuel tank or batteries instead of a number of fuel tanks variants; and changes to take place even more frequently than today. This puts extremely high demands on the ability to design, plan, schedule and balance a mixed-model systems in order to achieve and maintain an acceptable system performance. The increasing complexity puts great strains on the whole organisation and collaborating partners. The trend of increasing **frequency of changes** (both planned and unplanned) need to be addressed and handled in an organized way. Changes affect production operation as well as development processes requiring increased knowledge of: the types of changes that need to be handled; how the present way of working supports proactive and reactive ways of handling these changes; and how to utilize new knowledge gained in these situations for future similar situations [2]. Several issues related to complexity have been identified as critical for successful **product introductions** [3,4]: simultaneous assembly of both new products and existing products in the same assembly line, the degree of change in production system, utilization of new experiences and knowledge in new projects, cross-functional dependencies, and the ability to handle uncertainties and problems that occurred.

During design and development, production systems must be **optimized** from station and line level to plant level. Today basic knowledge and heuristic methods are available for planning and calculating in advance the **total man-hours** needed in different operations and applications. However, there is a lack of deeper knowledge regarding the contents of indirect work in these calculation models. This is a problem as the amount of necessary **indirect work** tends to largely increase with the degree of production complexity. According to Volvo Cars and Electrolux, it is becoming increasingly difficult to calculate the total man-hours needed for assembly (both direct and indirect).

The production system must continuously be **optimized and re-balanced**, due to changes in product mixes, volumes. To be able to cope with the changes, IT tools for line balancing are available to the industry. As the frequency of re-balancing and the complexity will radically increase, further development of methods and tools is required. For manual assembly operations, **standardized operation instruction** sheets are important for efficiency and quality assurance. Thus, increased production complexity is adding difficulty of developing and using work standards. Standardized work instructions are not easily maintained, updated or changed to new variants or stations. At the same time, quality requirements force stricter use of standards that stress the importance for leadership approaches to maintain and gain acceptance and ownership of standardized work procedures.

1.1 Research project focusing complexity

These industrial challenges stress the need to support analysis of complexity from the perspective of shop-floor/operation, line re-balancing, and man-hour planning. The higher flexibility a system has, the more difficult it is to achieve high efficiency. By managing complexity, it is possible to achieve high efficiency even though flexibility is high. Therefore, the notion of "production complexity" needs to be explored and defined. A **Vinnova-funded research**-project "Support for Operation and Man-hour Planning in Complex Production" (COMPLEX) is conducted from 2010 until 2013. The project is done in collaboration between Swerea IVF, Chalmers, Volvo Cars, Electrolux, Stoneridge Electronics, and AB Volvo. Industrial case studies at these are carried out to get empirical data and knowledge about systems, complexity, and needs for handling complexity. Members of the COMPLEX research team have since 1992 worked with manufacturing system's ability to adapt to constantly ongoing changes e.g. shorter lead time and faster change-over due to market requirements [4,5,6,7,8].

The project improves the ability in participating companies for managing production complexity. **Expected results** from the project are: an operational description of the "production complexity" concept; a method for measuring complexity; and models and methods to support line re-balancing, man-hour planning, as well as management of complexity, skills, competences, and information support. **Research questions** have been formulated for the COMPLEX project concerning the definition of production complexity, indirect man-hour work increase, competence and information support, and line re-balancing factors. These areas are considered significant for managing complexity. (RQ1) What should be included in a definition and description of "production complexity" to support measurement and development work of efficient, highly flexible and sustainable production? (RQ2) How are the different parts of the total indirect man-hour work affected by the increased complexity? (RQ3) What skills and competence and information support are required and how can this be provided, in order for production personnel to manage the added complexity? (RQ4) What factors should be included in a line re-balancing methodology and calculation models for man-hour planning?

1.2 Paper focus and organisation

The paper shows results from a literature study and initial steps of industrial studies that has been carried out during the project's first year. The paper also briefly presents the research project and objectives. In order to provide answers to the research questions, the research project will be based on case studies in the partner companies. As a starting point for the research, an initial case study at the partner companies was conducted. This paper reports results from this initial study, which will guide the main case studies later in the project. The paper is organized as follows. In section 2, the methods used are presented. In section 3, the industrial development needs are presented. In section 4, the literature findings are described. Section 5 discusses the findings in the literature and studies of industrial needs.

2 METHODS

In this section the methods used are presented. Included in this paper are the initial case studies at the industrial partner companies and the literature study conducted to capture industrial needs of complexity methods.

2.1 Case studies – study of industrial needs

The initial case study was aimed at gaining a better understanding of industrial needs and potential users of complexity models and methods. One aim was to certify that the continued research work will deliver results that are applicable to industry. Another purpose was to be able to delimit the literature study conducted in parallel, i.e. to clearly identify what issues relating to complexity that is focused by industry. Data collection of industrial needs was carried out through company visits, initial dialogue with company representatives representing production management, internal logistics, production engineering, operations, and man-hour planning, and a cross-organisational workshop. Production situation and trends were discussed. Experiences and challenges of increased complexity were identified, considering their needs for managing complexity. The research questions and complexity model requirements have been further elaborated at the three industrial companies involved in the project.

2.2 Literature study of available models and methods

The literature study covered relevant complexity research, definitions and perspectives of complexity, models of complexity considering different aspects of production, methods and models for measuring complexity, and means of visualization. Research conducted in the area of complexity is extensive, and as a consequence, the results available in literature are vast. However, research is mainly conducted from a theoretical perspective and not targeting production, assembly, or supply chain systems. The purpose of the literature study was not to provide a complete overview of complexity research, but to identify models and methods that may be used to build upon for the continued research. Thus, the study was delimited to models and methods which were applicable to industrial systems, and had potential to be used as a practical and realistic methodology in an industrial context.

3 INITIAL CASE STUDIES – INDUSTRIAL NEEDS

Volvo Cars, Electrolux and Stoneridge are three worldwide companies with production sites in several countries. All three companies have to maintain, or even increase, efficiency, flexibility, and sustainability of process and operation, despite coming challenges. Volvo Cars expects an explosion of product variants. The Electrolux plant in Mariestad will go through a large transformation during the next year and Stoneridge Electronics are operative on a very competitive market with fierce requirements on quality. The initial case study is very limited, only including three companies. Nevertheless, the results show that the companies have a very similar view of complexity management needs.

The companies stress that complexity models, methods and tools, must be practically usable and **easy-to-grasp**. The initial study of industrial needs states the need of a model that use **same language** for most parts of the production as well as be able to the model must be able to handle **manual, semi-automatic and automatic** production. It must also be possible to study and compare complexity with other production units, on workplace/station, cell/line and shop/factory level. The model must take a holistic grasp and be able to handle mix-model production within a single line and not sub-optimize production in favor of the supply chain. The study strengthened the initial assumptions made prior to the project's start: the following four areas are explicitly important in regard to complexity.

1. **Indirect man-hours** will be affected by increased complexity. With existing models it will be difficult to determine and control the amount of man-hours needed for indirect production work (repair, maintenance, meetings, management, training, etc.).
2. Planning and designing the production system of future products will be difficult as we **lack models and methods** for defining, comparing, and analysing concepts of different complexity, although this aspect is fundamental to future production system.
3. **Support of complex operation** becomes less efficient as today's tools for supporting ergonomics, quality assurance, work environment, competence management are insufficient
4. **Line-balancing** and re-balancing is vital for efficient performance in a mixed-model system. Available tools are not adapted to the required rebalancing speed or high number of variants possible.

4 LITERATURE STUDY

Concerning research on complexity, vast resources have been invested over the years aiming to define, understand, model, and develop methods to measure and manage complexity. The research reported in this paper attempts to identify relevant ideas, for the continued research work. In this section, an overview of the literature study results is given. To support the determination and understanding of the problem and to develop a feasible approach, the research is based on and guided by a theoretical base including mainly: (1) complexity science and complex adaptive systems, which provides models, methods, theories; (2) human cognitive skills, competence, skill/rule/knowledge based tasks, information exchange; (3) levels of automation, human-machine collaboration, disturbance management; that is a key for handling complexity; and finally (4) scientific management, lean production, and socio-technical system principles.

4.1 Complexity research and definitions.

The term "complex" is often used in everyday language to refer to the difficulty of understanding, analyzing or solving something. However, in a theoretical sense, the term is a property of systems that is composed of parts, the interrelations of which generate behaviour on system level which cannot be explained by studying each part and interrelation alone. The scientific base of complexity research is interdisciplinary and encompasses many theoretical frameworks. Complexity definitions are tied to the concept of a 'system' and the set of parts which have relationships among them; the system in focus may be from e.g. technology, biology, and life science. Key aspects of complexity are [9] the interaction of many agents, behaviour that is affected by memory or feedback, and phenomena that emerges on system level.

System size generally increases complexity, but it is dependencies rather than size that govern complexity. Some large systems may be analyzed and fully understood by analyzing the constituting parts, and thus not being complex. The interdependency and behaviour emerging on system-level are central for the definition. Therefore, "complex" is the opposite of independent, in contrast to "complicated" which is the opposite of simple. This is in accordance with the Latin etymology of the word: "com" together, and "plectere" to plait, braid, i.e. "to plait together" [10]. Another reflection is that science of complexity concerns the **synthesis process** of putting parts together and understanding the emerging behaviour of the whole system. This process can be seen in contrast to the traditional reductionist approach of research that decomposes system into parts to better understanding the parts [9]. The study reveals that many models and methods dealing with the complexity have been presented. Also in production and manufacturing research, a broad array of systems analysis concepts dealing with the complexity has been presented, a comprehensive review was presented by Ueda [11].

Often referred to as a starting point for complexity research is the work by Weaver [12] who stated that the complexity of a system is the degree of difficulty in predicting the system properties, given the properties of the system's parts. Further, in Weaver's view, there is disorganized complexity, where interactions are random (e.g. molecules in a gas), and organized complexity, where interaction between the parts are non-random. Complex adaptive system (CAS) is a theory that models systems consisting of parts, where all parts have adaptive behaviour. Key for CAS is that the part adapts and behaves depending on history, other interacting parts (which also adapts) or the environment [13]. Theories applied to production show that the systems certainly has emergent properties that cannot be referred to certain individual parts. Furthermore, production systems can be considered a CAS, and also must be considered to have an organized complexity [14].

4.2 Key aspects – static & dynamic complexity

When modelling systems complexity, there seems to be a common understanding in literature, to separate into models with and without dynamism. Blecker et al. [15] separate between "structural complexity", which is related to fixed nature of products, structures, processes, and "dynamic complexity", which is caused by external and internal sources within the operation, like variations in dates and amounts due to material shortness, breakdowns, insufficient supplier reliability. Frizelle [16,17] divides similarly into "static" and "dynamic" complexity, and Asan into "structural" and "behavioural" [18]. Asan further presents a list of characteristics for each of these. Characteristics for structural complexity are numerousness, variety, and strength of interactions, connective structure, and hierarchical structure. Behavioural complexity is characterized by dynamism, nonlinearity, deviation from equilibrium, history, adaptive, emergent structures, and self-organisation evolution.

4.3 Complexity causes

Most efforts done to say something about complexity in the automotive industry uses product variety as the main complexity driver [19, 20]. In the context of production complexity, the product is only one of many factors causing complexity. In addition, other factors seem to increase its importance as production is becoming more automated, effective, flexible, and products are becoming more advanced. Naturally, these interacting factors may be grouped in many ways. Calinescu et al. list factors causing complexity as [21]:

- **Product**: number of products, and for each model: structure, number/types of sub-assemblies, variants, cycle/lead times, lot size, type and sequences of resources (routing).
- **Plant/Shop**: structure, number/types/capabilities of resources, layout, set-up, maintenance, idle times, performance, process step, operating effort.
- **Planning** and scheduling: strategies, document number, content, timing, and priority, decision-making process.
- **Information** flow: internal (decision-making, team), intra-plant, external (other plants, suppliers).
- **Other** functions in organisation: training, political, etc.
- **Environment** variability: customer changes, breakdowns, absenteeism, data inaccuracy, rework, etc.).

It is difficult to see the whole picture of the effects of a product modification or introduction of a new product. From one perspective it, e.g. an early product realization phase, in may not effect the complexity much, but from a system perspective the effects can be far-reaching since these factors are highly interrelated [4], and may propagate in the whole process. For example, changing in just a small part of a product, may introduce more processes, need for new technology, more information, changes in organisation etc.

From en external perspective, there are several challenges that may cause fundamental changes causing complexity. These factors are related to e.g. globalization, new market requirements, restructuring within companies, labor market structures, and sustainability requirements. Consequently they have an impact on companies´ ways of organizing work, and may also challenge traditional relationships in the work place. [22] Thus, managing complexity factors need to relate to companies´ context, specific challenges and hindrances, impact of regression periods, shifts in automation levels, technology development, variety of influence of temporary personnel, shifts on ownerships of companies, approaches towards sustainability from a economical, ecological, and social/human perspective, impact of globalization, etc. The different factors causing complexity can affect both the static complexity (e.g. many product variants, information flow, complex routing) and cause dynamic effects (e.g. changes in product variants, interdependent processing steps). Calinescu et al. takes a overall perspective on manufacturing complexity, while most research is delimited to one of these factors, like product complexity modelling, static complexity [23], operators work process [24, 25], or planning and scheduling.

4.4 Levels of automation vs. complexity

Automation is one way to improve productivity and efficiency in manufacturing systems. However, automation also contributes to the system complexity, since automated systems are highly integrated with the current products, processes, information, resources, human tasks, organisation. Automation may make operator's tasks simpler, but at the same time increases the complexity of the system that must be managed, maintained, re-designed, etc. Therefore, when designing and re-designing such systems with interacting humans and technical equipment, special attention to complexity issues are required. The balance between the human and automation can be used as a design parameter, by determining a specific level of automation (LoA) in the manufacturing system [26]. Choosing the wrong level of automation may result in considerable investments without sufficient gain in manufacturing system capability and an unnecessary contribution of the overall complexity. Highly automated assembly systems tend to be rigid and complex. This decreases the system ability to handle predictable and unpredictable events. Complex systems are often expensive compared to the product flexibility achieved. However, according to Dencker et al. [27] well balanced level of automation can give competitive advantages. To determine appropriate task allocation with a span of various levels of automation in assembly operations a methodology named DYNAMO++ was developed and validated [28].

The taxonomy of LoA is a seven-step reference scale, for cognitive and physical LoA. LoA is defined as “the relation between human and technology in terms of task and function allocation” [29]. Frohm et al. [30] characterizes physical tasks by the level of automation for mechanical activities, **mechanical** LoA, while the level of cognitive tasks is called cognitive LoA. Mechanical LoA is with what to assemble, while **cognitive** LoA is information needed to assemble. The system complexity (incl automation system, humans and tasks) tends to increase with higher level of automation but the operator’s subjective complexity may be reduced by an effective provision of information support. Just as the LoA can be seen as an important design parameter, the level of complexity can be considered a parameter of the system which need to be considered during design

4.5 Direct and indirect work

Increased automation does not only replace manual work, it also adds work to be performed. New systems must be managed and integrated, and tasks like maintenance, education, set-up, break-downs etc. are added. In this paper, “direct work” refers to work conducted on the product (both main and sub-flow) and “indirect work” refers to all supporting work conducted to make sure the direct work is possible, e.g. maintenance, production engineering, quality control, management, etc. The content of “direct work” and “indirect work” is closely related to Rasmussens’ classic levels of performance, i.e. skill-based, rule-based, and knowledge-based behaviour, the SRK-model [31]. Shop-floor work tasks referred to as “indirect work” are for example problem solving/disturbance handling, programming, planning/ controlling/following-up, coordinating specialized areas, maintenance, mentoring/teaching/training, cross functional collaboration with customers/plants, suppliers worldwide as well as documentation and visualization of actions, results etc [32]. For these work tasks individuals in a higher degree have to rely on earlier experiences, and require to a higher degree “non-technical” skills and competences, such as analytical ability, ability to work well in teams, and overall understanding (company, flow, trade, customer focus) [32]. Hence, the assumption of that increased complexity may increase the proportion of “indirect work”, will increase the need to describe these work tasks and required skills and competences, information and support for organizing learning opportunities, training, validation of current skills and competences etc. Since competence and information support are important means to handle complex tasks, the SRK model and research may provide components that help to reduce or handle complexity in direct and indirect work.

4.6 Objective and subjective complexity

Increased automation and more indirect work makes more people involved in operations, all with different tasks, and perspectives in production [32,33]. For management of complexity, individual’s knowledge and capability of adapting the performance is central. For management of anyone’s work, perception of the system’s complexity is important. However, the same system and situation may be considered very complex by one person but not so complex by someone else. Therefore, it is important to consider not only the system’s complexity as it is, but also how it is perceived. This categorization of complexity is adopted by many in literature. Li & Wieringa [34] presented a conceptual framework for perceived complexity in supervisory control systems. The framework consists of three factors. First, the **technical system’s** complexity, divided into the complexity of human-machine interface and process & control system, respectively. This is determined by the types, numbers, variety of components, links / dependencies between components. Secondly, **task complexity** that is determined by the nature and number of tasks, and the links / dependencies, task arrival uncertainty and frequency of tasks. Thirdly, perceived complexity is determined by **subjective factors** like personal factors (knowledge, training, personal type, background, willingness) and operation and management strategy.

4.7 Complexity and information

Being one of the causing factors of complexity, information flow is essential both since it creates complexity and at the same time introduces possibilities of handling it. Appropriate levels of automation, both cognitive and physical, must be selected in order to cope with challenges caused by mass customisation and to handle the increase of complexity. In the ProAct project it was suggested that the interaction between levels of automation, competence and information, needs to be balanced in order to maximise assembly systems flexibility and the action space of the operator [35]. Urbanic and ElMaraghy [25] states that manufacturing process complexity is associated with the understanding and managing of large quantities and diversity of information. Furthermore, they present a model of complexity consisting of content, quantity and diversity of information for a process. Other theories regarding the complexity of information is Ensley’s information gap theory which, claims that more data does not necessarily result in more information [36]. Further, Kehoe argues that the effectiveness of information is based on quality not on quantity [37]. It stands clear that the information support system is vital for production system and needs to be considered as a parameter in relation to complexity.

4.8 Complexity entropy model

To model complexity, several models have been introduced. Shannon introduced the approach of Information complexity, using the term “entropy” which measures the uncertainty and randomness of a variable in the system. Since then, many have adopted the entropic modelling approach [23]. Maximum uncertainty/entropy makes it the most difficult to predict the outcome. Entropy shows the rate of variety among possible next states, as a system changes state [16]. Applied to production, the entropy of a production system can be applied to states of a station, the tasks/choices in station, or the line/system [38]. The entropy of an operation reflects how uncertain it is that the operation is the next operation in a station.

Frizelle and Woodcook [39] presented a entropy model for static and dynamic complexity of production, which is highly relevant, although theoretical. Frizelle and Suhov [16] developed this and tested a measure based on entropy. In conclusion they say it seems possible to compare systems using their entropy rates measurement. The entropy of a certain state in a machine is calculated based on the probability of that state to occur. This probability can then be associated with a number of possible states, e.g. probability of 0.125 is associated with 8 possible states. The entropy is the amount of information needed to document 8 states. Taking the binary logarithm of 8, gives us 3 bits of information is required. This entropy is then multiplied by the probability of that state (as a weighing factor for that state's entropy). The entropy of the station is the sum of all these weighed state entropies. The stations entropy may be summed up to obtain the entropy of the line.

Recent research in the area of mix-model production in the automotive industry has been carried out by Zhu [40]. They use operator choice complexity as their complexity measure and base it on information entropy of the average randomness in a choice process. They state a way to mathematically calculate station complexity that includes product variant, which results in part choice, fixture choice, tool choice, and procedure choice. When accumulating the measurements into line and system complexity the propagation of the variety is included for each station. Their calculations have been used for better understanding the manufacturing system complexity on performance as well as guideline for system design.

Abad has further developed their models of complexity calculations by introducing mathematical measures for production quality performance and "capability to handle the selected complexity", defined by input product variety. He chooses to see the production system as a communication channel between market demands and customer, and measures the noise of the channel, or process uncertainty by comparing input: product list (sequence list) with proper output: products ready to deliver. In addition he adds a factor for the influence of human performance based on the background that simulated results are often less accurate when representing production with large manual content. The operator's factor is built-up by choice task complexity (part mix ratio), autonomous learning (operators' experience) and mental deliberation (thinking time). These measures are then used for e.g. selecting system configurations, allocating cycle times to maximize process capability to handle complexity in an assembly line.

4.9 Information diversity, content and quantity

ElMaraghy & Urbanic, [24] have presented a model for complexity of products, process, and operations. The model has an information focus and proposes that three elements affect the complexity. First **diversity,** measuring uniqueness or a diversity ratio between the specific information needed for the task, to the total information (value betw. 0-1). Secondly, **content**, a relative measure of the effort needed (e.g. number of stages or tools) to perform the task (between 0-1). Methodology to calculate this is developed. Thirdly, **quantity**, absolute quantity of information needed using entropy measurement. A measure of **product complexity** is calculated by multiplying the product's information quantity with the sum of its diversity and its content. Complexity of each **process step** is calculated by multiplying its information quantity (entropy) with the sum of diversity ratio and the relative complexity coefficient (content). The relative complexity of a process step is calculated based on both cognitive and physical effort. The complexity of the whole process is the sum of the product's complexity and the sum of the complexity of all the process steps.

4.10 Knowledge and technology complexity

Meyer and Foley Curley [41] developed a method (MFC) for management of software development [21], introducing two concepts: **knowledge complexity,** which is the domain specific knowledge and decision making complexity, and the **technology complexity**, which is the underlying computer technology for developing the application. Knowledge complexity is assessed regarding decision maker's knowledge, information at hand, and the interpretation of these to make decisions. Based on interviews and questionnaires, seven variables are given scores, e.g. breadth, depth, rate of change of decision making domain. Calinescu et al. [21] compared Frizelle's entropic and MFC method. They conclude that the methods complement each other, and differ a great deal regarding what types of complexity they show, requirements, and methodology. The entropic method, although more time consuming and data requiring, provided more information of the system. However, the MFC method provided more information of the decision-making process.

4.11 Complexity Measurement / Visualisation

Schleich et al [19] presents a complexity cost model where the cost of complexity is related to (1) departments, (2) product variety, (3) variant drivers and their variants instead of emerged out as a total overhead on production cost. Urbanic & Elmaraghy [25] presents diagrams where alternative solutions for process are compared: CNC, dedicated machinery or a combination. Blecker et al. [15] presented a methodology to measure structural and dynamical complexity on the whole supply chain. The visualization of the structural and dynamic complexity using a spider graph, could certainly be adopted also to complexity in production.

4.12 Complexity management

The uncertainty of what is the outcome of a process is a key to its complexity. Human cognitive skills at different levels in the organisation are increasingly crucial when production systems are becoming more complex and subjected to changes and uncertainties [42]. In complex environments, unknown events are assumed to increase and are by Reason and Hobbs [43] referred to as **novel** problems, while known events usually are routine and **trained-for problems**. Thus, the added complexity increases the needs for supporting ergonomics, work environment, competence management, assembly instructions, and training facilities and support.

From the studies of product introductions, it is also clear that **pre-series** production has an important role to facilitate learning and competence development [7]. These activities create **arenas** where involved personnel meet and discuss common topics, which provide opportunities for learning by doing and learning through experiments [44, 45], and are examples of necessary "indirect work" in production. To round off the literature survey we look at management of product, process, information etc. variety to reduce costs, and increase flexibility and efficient. But, what are the costs of complexity? MacDuffie, et al presents a great effort to empirically calculate the relation between product variety and assembly system performance based on data from appr. 70 assembly plants worldwide [46]. However, the results show no clear evidence for any of the relations analyses in the study. The authors indicate that companies should focus on smart ways to handle complexity to get variety "free of cost".

Some authors present models separating product complexity as one dimension and production complexity as another [47]. Studying a specific plant and product may then allow for identifying production having high / low complexity vs its products, which may have high / low complexity. This is a tool to better identifying appropriate focus for complexity management. Corbett et al presented a route map for complexity management, in which structural complexity is simplified and dynamic complexity is managed and controlled. Two levels of management are mentioned **prevention and cure** [48]. Kaluza et al. [49] presents a model of four strategies for handling complexity: **accepting, controlling, reducing,** and **avoiding** complexity. According to Grote [42] adequate management of uncertainty in complex systems is crucial for safe and efficient system design. Rules management and complementary system design are pointed out as two particularly promising avenues for uncertainty management, and depends to a high degree on the systems designers and planners understanding regarding the roles of humans and technology in handling uncertainty.

5 DISCUSSION

Based on literature study and industrial needs, the research team emphasizes a number of aspects: (1) **Unknown events** are assumed to increase with complexity, requiring support from ergonomics, work environment, competence management, assembly instructions, training facilities, and support. (2) **Perceived complexity** is important as it is governs the users work performance and identifies what support are needed for the user. What is perceived complex depends on competence, information, and situation? Considering the role of **humans** and technology in work systems is crucial for coping with uncertainties. The **user's perspective** of the system is considered important. Different functions and roles have different tasks and system view, and thus different view of complexity and needs for support. (3) There is need for approaches that support **coping with complexity**, as complement to reducing complexity; **Management of uncertainty** in complex systems is increasingly important – considering the role of humans and technology in work systems is crucial for coping with uncertainties. (4) Complexity model must take a **holistic** view including all causing factors (the plant and resources, products, processes, people, technology, information, etc); and both direct and indirect work. The need to find a **simple** model and measure of complexity, which is accurate enough for the purposes set up. The base for such measure/model may be formed by a combination of published models.

5.1 Complexity framework

To sum up the literature survey, we understand there are a multitude of models and methods available for further evaluation. The research project must take a **holistic** perspective on the modelling and management of complexity. Therefore it is considered important to study the whole production, including also the **indirect work** related to the direct work performed in production. Also vital is to include many **causing factors** (products, process, information, etc.) since the interaction among these is important. A fundamental problem of defining and modelling complexity is that it involves **many aspects** and therefore is difficult to grasp in one single model. A vital part of the difficulty in product and production development is that just modifying a product seems not to increase complexity much, while the effects can be far-reaching since the causing factors are highly interrelated [7]. This holistic perspective also manifest in the need to not look at the technical and physical systems isolated, but to see them as a very much interrelated with all **people** and the organisation.

The target of the research in the COMPLEX project is to develop a common understanding of the **concepts of complexity** and possibilities to measure, communicate, and compare. An analogy is made with the methods and models previously developed for measuring the level of automation of operations. The fuzzy concept of automation level was thus made measurable and easier to communicate and manage. An idea is therefore to make also the concept of complexity more clear and to be able to evaluate a system's "level of complexity". Doing that, it would be possible to manage complexity.

Many of the perspectives and focuses of complexity identified in literature are considered relevant for the purposes of the research. First, the categorisation in **static and dynamic** complexity seems to be a commonly agreed way to consider complexity. Static complexity may reveal much of the system's complexity. But, as the world is dynamic, this is not a true picture of the system. It only provides basic information for the real complexity, like a measure of the production's potential complexity. The dynamic aspect of complexity is what makes the system really hard to manage. Both the characteristics of static and dynamic complexity may play a role in a practical measurement of a complexity models and methods.

The **entropic** modelling approach also seems to have gained a broad acceptance in literature. The models are theoretical and mathematical and difficult to comprehend, but have been evaluated in case studies. It has been applied for production systems, and includes product variety, production system configuration, and human performance. We believe that in some form entropic models can be applied also in a more easy-to-use complexity model / methods. Also extracted as relevant for continuing research work is the categorization into **subjective** and **objective** complexity. To ask users within the system for their individual experience of complexity, can be seen as a way to collect and incorporate all the various interacting, factors, subsystems, etc. in the system. Subjective complexity is thus an effective method to bring many aspects together. But we argue that the use of subjective complexity is required, since a system's objective complexity only, in a way, provides a hint of the complexity as it is experienced by various users. Furthermore, subjective complexity is by definition easy to accept and interpret by the users. Using subjective complexity complements the theoretical definition of complexity, i.e. theoretically un-complex systems may be considered very complex, or complicated by users.

A result from the work is the identification of **roles** needing complexity support: line re-balancing, operators, production engineering, and man-hour planning. Literature also presents many interesting ways to **visualize** complexity that can be utilized for the work in the COMPLEX project. The literature further gives different models of complexity **management**: minimizing, reducing complexity causes on the one extreme and accepting, and coping with the complexity on the other extreme. In the literature study we found no models about the influence of complexity on indirect time needed in the production systems. Neither is there yet any remedies or methods/tools suggested for coping with complexity, nor suggestions for how to use the measurements in an industrial setting. Also the "**easy to use**" factor has a lot more to wish for as it would require some sort of commercialized simulation system to be introduced in an industrial setting.

As a way to comprehend all the views, models and theories, and to clarify the continued work of the research, we proposed a framework depicted in Fig 1. In this the complexity causes [21] that act on the production system is the foundation. These causes may be initiated by external changes (e.g. new product, equipment), or from within the system (e.g. schedule or routing changes). The static complexity of the system or parts of it can be modelled using a modelling approach like e.g. entropic modelling (production flow, stations, etc, or only some aspects, like information, product, routing etc.). The dynamic complexity is modelled in order to include the time and dynamics (like deviations from plans, uncertainty). Both static and dynamic complexity are objective. To include more aspects and involve several roles' view of the system, the subjective complexity must be modelled. The impact of complexity on the organisation (technology, man, organisation, methods, tools, etc.) may also be considered a layer in the framework. The various management methods, like reducing, coping, supporting, etc, and tools like measurement, visualization, etc can be seen as a top layer depicted in Fig 1.

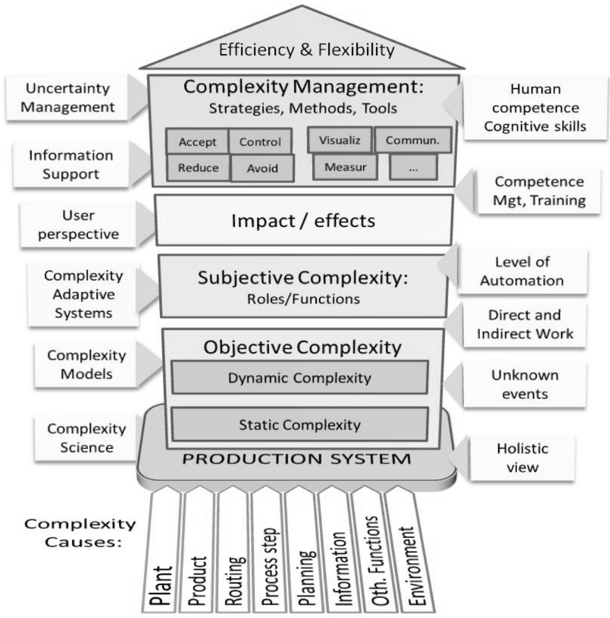

Fig. 1: **Complexity framework.**

6 CONCLUSIONS

This paper presents a research project targeting production complexity. It reports results from an initial case study of needs relating to complexity management, among the industrial partners in the project. Also reported is the result from a literature study conducted on the topic. The results are organized into the model presented in Fig 1 which is a suggested framework for dealing with complexity. The model provides structure to models and ideas found in the literature and industrial study. Important findings are: (1) **unknown events** increase with complexity; (2) Management of **uncertainty** is increasingly important; (3) Considering the role of **humans** and technology in work systems is crucial for coping with uncertainties; (4) There is need for approaches that support **coping with complexity**, as complement to reducing complexity; (5) A model and method to describe and measure complexity must be **easy** to understand and use. The base for a complexity measure/model may be formed by a combination and adoption of several published models, many of which having a theoretical view of production; (6) Complexity model must take a **holistic** view including all causing factors and both direct and indirect work; (7) and include different **user's perspective** of the system. Different function, role have different tasks and system view, and thus different view of complexity and needs of support; (8) A complexity model and method should separate **subjective complexity** from objective complexity, which is a property of the. Subjective complexity is important as it is governs the users work performance and identifies what support are needed for the user – what is perceived complex depends on competence, information, and situation; (9) A complexity model and method should separate **static complexity from dynamic** complexity, which includes uncertainties, variation, and changes.

These conclusions will guide the design of methodology for the further case studies in the project, e.g. to clearly separate the studies of objective and subjective complexity. The model will also be the base for further development of models and methods that support the users/tasks targeted in the project: man-hour planning, rebalancing, and complex operation tasks.

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