AN EMPIRICAL STUDY TOWARDS A DEFINITION OF PRODUCTION COMPLEXITY

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Abstract

Mass customisation increases the number of product variants, shortens product cycles, and results in increasingly complex production systems. The complexity needs to be defined, and further operationalized to support management of production complexity. This paper's contribution is the empirical findings of perceived production complexity at three manufacturing companies, from the perspective of different functions/roles within the production systems; production engineers, operative personnel, internal logistics, and in one company also man-hour planning. Data was collected through observations, interviews, and cross-functional workshops. Results show that mass customisation is the greatest driver and cause of complexity. The increase of product variants affects complexity for all three investigated roles in the production system.

Keywords:

complexity, manufacturing, parameters, subjective, management, roles

1 INTRODUCTION

Future production systems need to be extremely flexible but still remain and excel their efficiency. Mass customization of consumer products increases the number of product variants, shortens product cycles, and frequently results in increasingly complex production systems. This is a major contribution to complexity. Assembly complexity is further increased by new product requirements such as hybrid engines. In order to handle challenges related to production complexity new support is needed for measurement and development of work towards efficiency, highly flexible and sustainable production. The production complexity in assembly systems therefore needs to be defined, described and broken down into relevant components that can be used for measurements, analyses and support tool for development.

This work is part of the research project COMPLEX, "Support for Operation and Man-hour Planning in Complex Production", conducted from 2010 until 2013. The overall focus is to reduce complexity by developing generic models and methods to support strategies, planning, managing, and optimizing of complex production. A theoretical framework for complexity was proposed [1], Figure 1. This paper aims to further develop this framework by empirical studies including three case studies in companies with production complexity challenges. In specific, production complexity parameters are investigated from a company and an individual perspective. The case study approach enables mapping of how complexity is perceived by different functions in their work with operations, re-balancing, internal logistics, and man-hour planning. Furthermore, the empirical studies enhance the modelling and development of management of production complexity, development of appropriate information and IT-support tools for calculation of the total requirement of indirect and direct man-hours in production, as well as competence development approaches.

2 THE PRELIMINARY FRAMEWORK

The proposed framework based on a literature study takes a holistic view on production complexity acknowledging the need to account i) complexity drivers; causes/complexity parameters, ii) the production system context, iii) objective, and subjective complexity, iv) impact and effects of complexity, and v) complexity management [1].

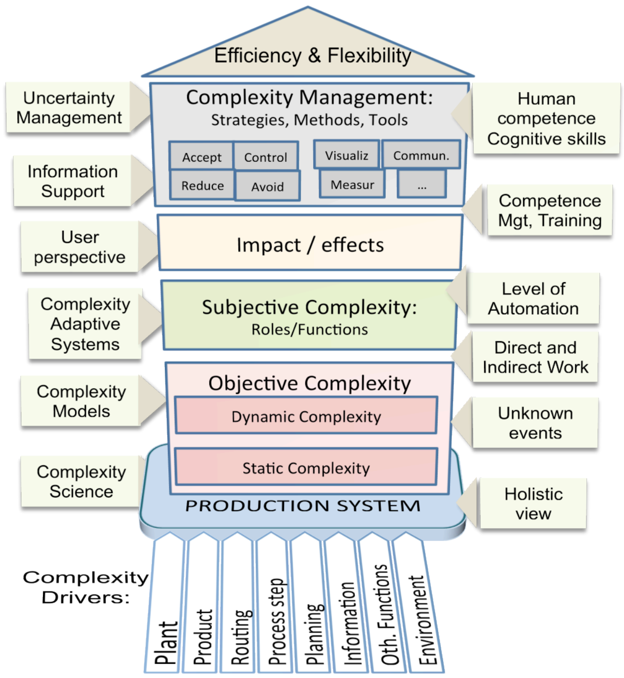

Figure 1. Complexity framework [1]

In the context of the production system, complexity parameters; drivers, causes and effects may be initiated by external changes (e.g. new product, equipment), or from within the system (e.g. schedule or routing changes). There are several factors causing production complexity, which can be operationalized as production complexity parameters.

Previous research emphasise different drivers of complexity in a production context. The relationship between complexity, and variety of products has been investigated by several authors [2-4], and has been referred to as the main driver for complexity within the automotive industry [3]. MacDuffie *et al* makes use of four measures of variety in their complexity model targeting the automotive industry: model mix, part variation, level of content and variability of options [2]. Urbanic *et al* put forward another model where the quantity, diversity and content of information are used as a function related to complexity [5]. Calinescu *et al:s* list of factors causing complexity was used as a basis to form the complexity parameters in the framework. The parameters are: products, plant/shop, planning, information flow, other and environment as seen in Figure 1.

Regarding *objective production complexity*, measurable parameters are important since they provide a hint of complexity as several experiences it and independent of whom the user is. Objective data can capture both dynamic and static aspects of complexity (Figure 1). The static complexity of a system or a sub-system can be modelled measuring parameters such as number of stations, work tasks, parts, levels of automation etc. The dynamic complexity is modelled in order to include time and dynamics, like deviations from plans, and uncertainty. The objective data focus of this paper is on static objective data rather than dynamic.

Regarding *subjective production complexity*, the same production system or situation may be perceived differently depending on a number of different factors such as individuals´ skills, competence and experience. Perceived complexity is in research closely related to managing and handling critical events, production disturbances, frequent changes, unknown situations, unpredicted situations, and difficult work tasks etc.[6-8]. Hence, as production systems become more complex there is more that can go wrong, in several ways, and it is increasingly difficult to predict faults [9]. Human cognitive skills at different levels in the organization are increasingly crucial when manufacturing systems are becoming increasingly complex and subjected to changes and uncertainties [10]. Also development of both reactive and proactive ways of working are needed where many different functions need to collaborate [11].

To grasp the perceived production complexity it is therefore necessary to gain an increased understanding of different functions and their needs in the organization [12]. There is also an increasing collaboration between different functions while handling changes and uncertainties during different phases of product realization [6, 13-15]

Regarding *impacts/effects,* the impact of complexity on the organization (technology, man, organization, methods, tools, etc.) needs to be considered. Challenges related to globalization, market requirements as well as handling critical events during product realization needs to be addressed from a *complexity management* perspective. To run a manufacturing/production system of large scale is a challenging task that requires competent people from different fields of expertise and organizations to join forces, efficiently and effectively. The increased complexity also challenge man-hour planning, on plant, line and station levels, as the indirect work tasks will increase while being insufficiently specified [1]. According to Grote [16] adequate management of uncertainty in complex systems is crucial for safe and efficient system design.

3 CASE STUDIES

Three case studies have been performed at three plants located in Sweden belonging to three global companies: Volvo Cars Corporation (Case A), Stoneridge Electronics (Case B) and Electrolux (Case C). All companies had similar challenges to maintain and increase their, efficiency, flexibility, and sustainability of production, which will be needed to address coming challenges [1]. The case studies have been performed during the fall and winter of 2010.The case study contains of five steps, illustrated in figure 2.

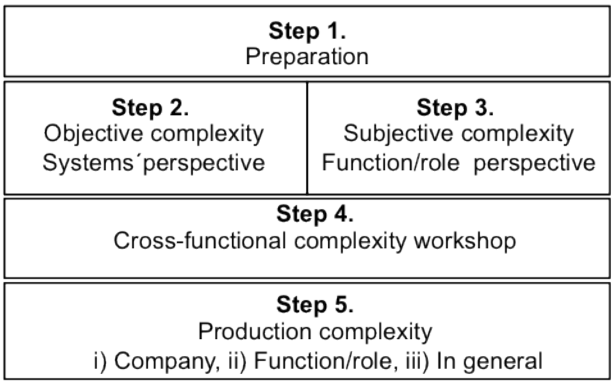

Figure 2 Case study approach

Step 1. Preparation – Initially, the research team planned the study in collaboration with representatives from the company. In this phase, the companies´ needs related to production complexity were defined, followed by a selection of a production unit for the case study. A production unit (a team area/cell) within the final assembly was selected by company representatives and formed the physical platform for the study. The production unit was selected based on that it was experienced as challenging and future complexity challenges were expected.

Within each company, a production unit, and two stations were chosen for further analysis; one station considered to have a high degree of complexity and one station considered to have a low degree of complexity. This was done so that comparisons between the stations easily could be made. The choice of stations was done in accordance with the representatives' perceived view of complexity, which facilitates comparison of subjective and objective complexity. Additionally, an interview guide was designed, participants from the company were identified.

Step 2. Objective complexity (Systems´ perspective) – Quantitative data was gathered using the first two steps in the DYNAMO++ methodology [17, 18] and the further developed concept model [19]. The selected production unit was studied by "walking the process", carrying out open interviews with production technicians, internal logistics and production employees. Further, observation of the two selected stations where done by filming and photographing, this data was then analysed further in accordance with DYNAMO++, i.e. measure Levels of Automation (LoA), both physical and cognitive in the chosen tasks and stations within the cell. The data collection focused on information of the product flow, product variants and families, the Level of Automation, work tasks, time parameters on task, on a station/cell level.

Step 3. Subjective complexity (Function/role perspective) – Semi structured interviews were carried out with representatives from operations, internal logistics, production engineering, and from one company, also man-hour planning. The interview guide addressing perceived complexity aims to identify subjective complexity parameters, which was related to work tasks, actions taken to minimize or handle complexity, causes and effects/consequences, ways of working, challenges, etc. The interview guide was adapted from a framework developed for investigation of major planned changes in production from the perspective of different functions/roles [6, 7].

Step 4. Cross-functional complexity workshop – An industrial workshop was carried out, also video recorded. The data collection focused on causes and drivers of complexity from the perspective of operations, internal logistics, and production engineering. The semi-structured interviews combined with a cross functional dialogue facilitated analyses of perceived complexity from different functions, i.e. roles or departments within the production system; 1) production engineers, 2) operative personnel in the selected production area, and 3) personnel from internal logistics.

Step 5. Analysis of production complexity related to i) each company, ii) function/roles and iii) in general

Results are based on interviews with selected individuals representing different roles and occupational groups. This study included views from operations, production engineering, Internal logistics and, in one company, man-hour planning. The interviews and the workshops were analysed from a company and a role perspective, while the objective data aims to explain the context in which the complexity exists within.

4 RESULTS

All companies had similar challenges to maintain and increase their efficiency, flexibility, and sustainability of production, which will be needed to address coming challenges. The main challenge for case company A is to maintain or even increase efficiency, flexibility, and sustainability of process and operation even with the expected explosion of product variants. The number of components is expected to increase by 50% to 100% within the next three years, and the frequency of changes will increase compared with today. Also the product variants are getting more differentiated. This puts extremely high demands on the ability to design, plan, schedule and balance a mixed model system in order to achieve and maintain an acceptable system performance. It also has a crucial impact on the whole organization and collaboration with different partners.

Case company B is a global company with customers within the heavy trucks and automotive industry, which is a very competitive market with fierce requirements on quality. Therefore, it is of greatest importance to continually improve the production process in order to stay competitive. The challenges associated with complexity are mainly related to an increasing number of product variants, requirements on quality and volume flexibility.

Case company C are operative on a very competitive market with fierce requirements on quality, and the studied plant will go through a large transformation during the next year. The layout will be dramatically changed and new material supply systems will be introduced.

In all three companies, sections within the final assembly have been chosen for further analysis.. The reason for this is that the effects caused by an increasing number of variants are most apparent in final assembly operations.

4.1 Case Study A – Volvo Cars Corporation

Objective complexity – The layout was a takted line containing seven assembly stations. The operators assembled three different products but with 72 (high complexity station) and 32 (low complexity station) variants. Further, in the higher complexity station, more work tasks were performed and there were more variance between the different variants compared with the station with lower complexity. The higher complexity for parts was handled by the use of ergonomic help tools such as lifts, and pick-by-light solutions were used to handle the part complexity. Unexpectedly the cycle time was more evenly distributed at the complex station in comparison to the low complexity station were the cycle time varied greatly.

Subjective complexity – In case company A the perceived complexity was described by representatives from production, production engineering, logistics and man-hour planning. The general production complexity parameters were related to variants, volume fluctuation, the layout, visual indicators, e.g. pick-by-light, ergonomics, changes, deviations and manning, see Figure 3.

Production engineering (PE) specifically addressed the production complexity related to the product platforms, rebalancing, and development of technical support (physical and cognitive automation) for the operators and work in preparation phases. A challenge was the balance of support and flexibility, where stations with a higher degree of assembly support tools were less flexible, and minor changes were harder and more expensive to make. Production focus on: remembering how to assemble the different variants, especially the unusual variants. While internal logistics focus on material handling, foremost how to place the components most effective at the stations.

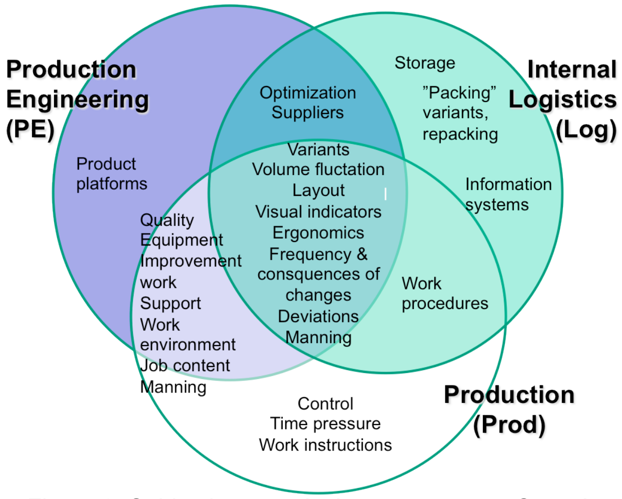

Figure 3. Subjective complexity parameters – Case A

The IT support system was not considered to be adapted to the large amount of variants and variant structure. Representatives from production (Prod), considered the main causes of complexity as the amount of tasks to be performed within a limited workspace regarding both time and space, the need to remember how to assemble different/unusual variants, and the uneven work pace caused by the many number of variants. From the perspective of internal logistics (Log), production complexity was foremost related to how to place the components most efficiently at the stations, i.e. storage, packing/repacking, information systems, and work procedures. In addition to the complexity parameters in figure 3, the company representatives responsible for man-hour planning (MHP) stressed challenges related to different time horizons. MHP specifically focused a long term perspective, i.e. 1 – 5 years, while PE focused a medium perspective (up to 1 year), and production a short term, daily perspective of daily – weekly planning. Further, complexity parameters were from a MHP-perspective related to variants, frequency of new/modified products, increasing product complexity, volume fluctuation, and production planning.

4.2 Case Study B Stoneridge

Objective complexity – Results from “walking the process” revealed that both chosen stations were within U-cell layouts. Each U-cell assembled one specific product family. This decreased the perceived complexity for the operators due to a reduced number of products to assemble. Both U-cells were not takted, operators had to plan the takt time themselves based on the number of pieces demand, hour and shift.

When measuring objective parameters such as number of tasks number of variants etc., differences were found between the U-cells. The low complexity U-cell produced five variants to customer from two motherboards, batch produced earlier in the value chain. But 90 % of the orders were of the same variant. The cell was characterized by stable, low product volume operated by one operator, thus easy to plan. The U-cell with higher complexity produced eleven variants of products to customer, created from four motherboards. It had a higher product volume with higher variation between the variants and volumes, more difficult work tasks, and more personnel in the cell to account for. More material handling and set-ups was needed compared to the low complexity cell. The number of tasks to perform on the two compared stations was 15-20 tasks in the high complexity station and 26 tasks in the low complexity station. The high complexity station had more cognitive support functions and advanced fixtures i.e. higher cognitive and physical Level of Automation (LoA), compared to the low complexity station.

Subjective complexity – In case B, perceived complexity was described from representatives from production, production engineering, and logistics. The general production complexity parameters were related to products/variants, the layout of the plant, and material planning, Figure 4.

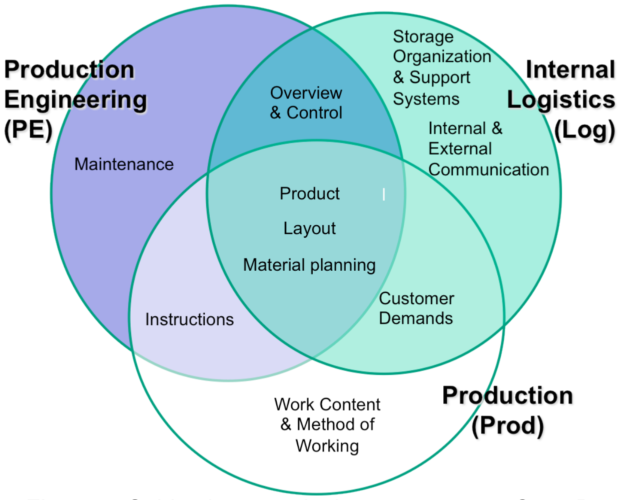

Figure 4. Subjective complexity parameters – Case B

Production engineering (PE) specifically addressed complexity related to sharing of resources, the material flow to the stations and machines. Further PE addressed overview and control, maintenance, and work instructions. Representatives from production (Prod) saw that the main causes of complexity were the distances between functions and the amount of machines. Further production personnel addressed the customer demands, work content and methods of working/work procedures, and work instructions. From the perspective of internal logistics (Log), production complexity was related to the lack of space for supermarkets, the material flow to the stations and machines, as well as a plant perspective of logistics including deliveries to the warehouse. Further, logistics addressed challenges related to customer demands, overview and control, storage organization, support system, structure of material, as well as internal and external communication.

4.3 Case Study C Electrolux

Objective complexity – The case study has mapped the whole assembly system, divided into five sections (or sub-systems). The analysis had a deeper focus on the so-called base assembly, which includes the first nine stations of the whole line (in total 37 stations). Each workstation was analysed and documented by "walking the process". The assembly lines were visualized to bring a rigid understanding of each defined action and transportation that were executed in the production flow. The cognitive instructions placed along the line at each station where used as framework, even though the operation sequence performed by the operators many times differed from the standard instruction.

The low complexity station had very simple operations that did not vary much between variants. The station with higher complexity contained more advanced operations. These operations required more knowledge about effects of the work performed. In addition, the shape of the component making the assembly work more complicated. The same cognitive supports were provided at all the stations even though the work content varied.

Subjective complexity – In case C, perceived complexity was described from representatives from production, production engineering, and logistics. The general production complexity parameters were related to products/variants, the layout of the plant, and material, Figure5.

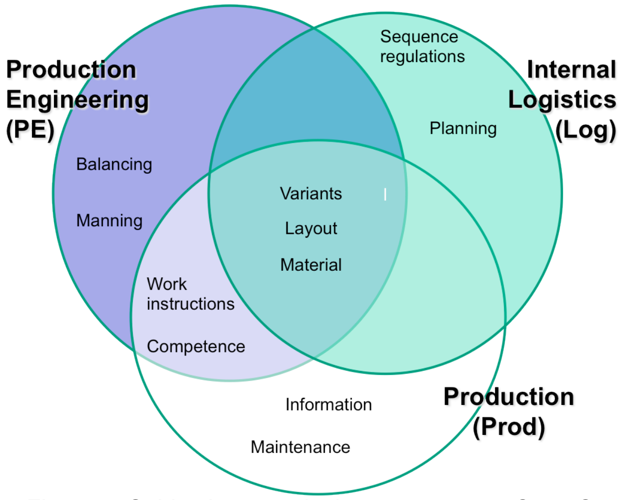

Figure 5. Subjective complexity parameters – Case C

Production engineering (PE) specifically addressed the material handling challenges linked to the variants. The balancing was affected by the variants because all of the models did not require the same manning of stations.

Representatives from production (Prod), found the main causes of complexity to be the scattered information about changes in product and the production line. The assembly work itself was considered quite easy but all of the operator were experienced and could be considered experts. Even though the work tasks were considered easy there were still a lot of variants regarding how the tasks were performed. There was a well-defined "best practise" but the operators still performed the task their own way.

From the perspective of internal logistics (Log), production complexity was related to the shape of the components. Today the logistics are well defined, but in the near future the whole concept will be changed into "train concept".

5 DISCUSSION

In understanding complexity further each companies´ specific challenges were further investigated from different functions perspective. Previous research have emphasised a clear focus on product variety as a cause and driver of complexity [3, 4]. The findings of the case studies described herein are consistent with that, but also indicate that a distinction needs to be made between objective and subjective complexity. The results from interviews and workshops clearly state that a holistic approach needs to be made in order to capture the cause and effects related to production complexity.

5.1 Subjective and holistic perspective

Depending on the individual function and role, the perceived complexity may differ, and the concept of production complexity is described from different time and abstraction levels such as task, station, cell, plant, and business unit/company level. For example, production engineering was mainly affected during ramp ups and re-balancing while assembly operators and internal logistics experience the production complexity more continually. Using subjective description of production complexity complements the theoretical definition of complexity, i.e. theoretically un-complex systems may be considered very complex, or complicated by users. This can be dependent on subjective factors for example previous experience, knowledge, training, personal type, background and mind-set. These variations between individuals needs to be regarded as well as the work tasks needed to be performed. Therefore it is important to capture objective and subjective parameters in order to get a better view of how a problem occurs, how they affect different functions in the production flow, and how production complexity can be managed.

5.2 Complexity parameters

The production complexity parameters, common within all three cases were i) number of variants (which were identified as the main driver of complexity in all three cases), ii) the layout, which was a mean for handling the complexity induced by all the variants, iii) material supply, which was an increasing challenge when the number of parts increase and the batch sizes decrease, and iv) ergonomics and human aspects both physical and cognitive.

They will contribute and expand the theoretical model, Figure 1. However it was seen that customer-oriented assembly and mass customisation are increasing in industry and this is one of the greatest driver and cause of production complexity. This leads to an increase in product variants, which has effect for the three investigated roles in the production system:

- Production engineers – Increased need for advanced methods to rebalance the assembly lines
- The chosen production area – Increased need for better and more functional information flows and to plan the production flow and levels of automation in order to avoid or cope with the increased complexity.
- Internal logistics – Increased need for material handling efficiency.

5.3 Complexity management

The companies had different strategies to handle and manage production complexity. All companies addressed the significance of the layout as a crucial complexity parameter. Company A and C had driven lines with a mixed model assembly, which seemed to cause similar complexity issues regarding balancing, material supply and information support. Company B had reduced the variant complexity by having one U-cell dedicated for each product family. This had different effects for different functions. Production engineers developed technical support (physical and cognitive automation) for the operators at more than one place, thus increasing the cost. Internal logistics had increased challenges with material handling, with more stations to support. This indicates that the production complexity has been shifted from assembly operations towards production engineering and internal logistics, but it is perceived as being easier to handle in this form. Results from the case studies shows that production complexity management needs to regard: i) Global perspective/external challenges, ii) Abstraction level; company/plant, cell, station, task level, iii) Time perspective; Short, medium, long term, and iv) Individual perspective; Function/role/work task. This is illustrated in figure 6.

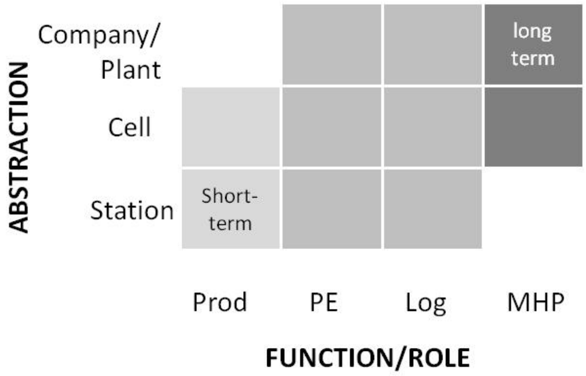

Figure 6. Subjective complexity dimensions

A holistic view needs to be addressed to avoid sub optimisation. If only focusing on one part of the systems complexity, other part of the process might have to endure an increased complexity. One example is the increased need of cognitive support tools to decrease the complexity for assembly personnel. The side effect is an increase of complexity for production engineers who have to manage the extra work associated with these solutions. Kitting could be seen as another example where the complexity has been shifted from assembly to internal logistics. By combining knowledge of both objective and subjective complexity parameters, production complexity can be visualized and measured supporting proactive work. The case studies supports the need of considering different functions and roles in order to get a holistic view of production complexity, illustrated in Figure 7.

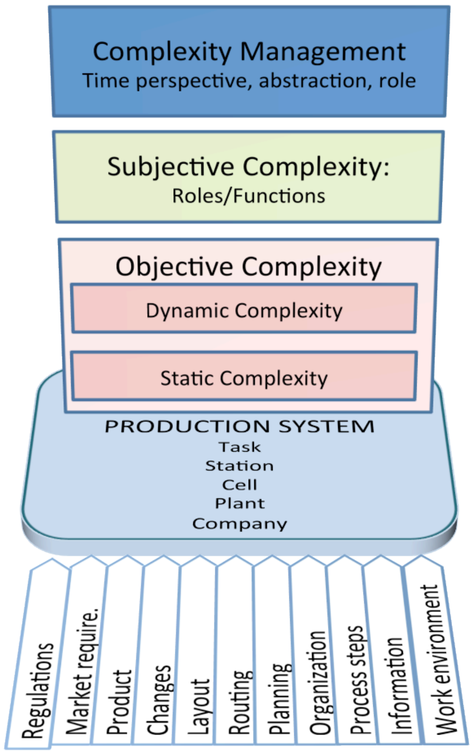

Figure 7. Updated parts of the complexity model

The model in Figure 7 presents additions to the discussed sections of the earlier presented complexity framework. The complexity parameters have been updated based on findings of this empirical study. Another focal point in the model is the need to consider time, role and abstraction levels when managing the production complexity.

6 CONCLUSIONS

The scope of the research project was to contribute to the preliminary framework of production complexity based on a literature study and initial identification of industrial complexity challenges [1]. By additional case studies in three companies, production complexity parameters were investigated. The empirical investigation supports and strengthens the proposed complexity framework by verifying and extending the main complexity parameters: and thereby investigating the drivers, causes and effects of production complexity. Furthermore the study identified the importance to take account for different roles within the production system when addressing complexity. Many complexity parameters are common for the different roles, although the viewpoint on the same parameter can be different regarding time horizon and abstraction level. Methods aiming to visualize, measure and reduce or handle complexity must acknowledge effects for different roles, time perspectives and abstraction levels in order to avoid sub optimization. The empirical study concludes that a holistic view needs to be addressed if the entire complexity is of focus.

The production complexity framework discussed in this paper will be further used within the COMPLEX research project to support complex operation, line rebalancing, and man-hour planning. In specific, following areas of research are planned:

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Gullander, P.,A. Davidsson, K. Dencker, Å. Fasth, T. Fässberg, U. Harlin, and J. Stahre (2011) *Towards a Production Complexity Model that Supports Operation, Re-balancing and Man-hour Planning*," In The 4th Swedish Production Symposium (SPS), Lund, Sweden.

[2] MacDuffie, J.P., K. Sethurman and M.L. Fisher, "Product Variety and Manufacturing Performance: Evidence from the International Automotive Assembly Plant Study," *Management Science,* vol. 42, pp. 350-369, 1996.

[3] Schleich, H., L. Schaffer and F. Scavarda, "Managing Complexity in Automotive Production," in *19 th International Conference on Production Research*, 2007.

[4] Hu, S. J., X. Zhu, H. Wang, Y. Kkoren (2008). Product Variety and manufacturing complexity in assemblysystems and supply chain. *CIRP Annals, Manuf. Techn*, 57 45-48.

[5] Urbanic, R.J., H. Waguih and H.A. ElMaraghy, *Modeling of Manufacturing Process Complexity*, 2006.

[6] Fjällström, S., K. Säfsten, U. Harlin, and J. Stahre (2009). Information enabling efficient production ramp-up, *Journal of Manufacturing Technology Management*, vol 20, no.2, pp 178-296

[7] Harlin, U., M. Berglund, and P. Gullander (2007). *Critical Events and Facilitation Factors for Realization of Planned Changes*, In proc. of The Swedish Production Symposium. Gothenburg, Sweden.

[8] Ylipää, T. and U. Harlin, (2007), *Production Disturbance Handling - A Swedish industrial survey*, In proc. of The Swedish Production Symposium (SPS), Gothenburg, Sweden.

[9] Hedge, J.W. and W.C. Borman, "Personnel Selection and Training," in *Design of Work and Development of Personnel in Advanced Manufacturing*, Salvendy, G. and W. Karwowski, Eds., New York: John Wiley & Sons, Inc., 1994, pp. 187-218.

[10] Grote, G., "A participatory approach to the complementary design of highly automated work systems," in *Human Factors in Organizational Design and Management—IV*, Stockholm, 1994, pp. 115-120.

[11] Säfsten, K., U. Harlin, S. Fjällström, and M. Berglund (2008). *Proactive and Reactive Ways of Managing Product Introduction*. In proc. of the 2nd Swedish Production Symposium, Stockholm, Sweden.

[12] Moestam Ahlström, L., Prerequisites for Development of Products Designed for Efficient Assembly – a study about making knowledge productive in the automobile industry., Ph.D. Dissertation, Dept. of Production Engineering, Royal Institute of Technology, Stockholm, Sweden, 2002.

[13] Harlin, U., P. Gullander, R. Lundin., F. Wandebäck, and M. Berglund *(2011)*, *Development of industrial work of the future – a study of Swedish manufacturing companies*. In The Swedish Production Symposium, Lund, Sweden.

[14] Berglund, M., On White-Collar Work Close to Production, Linköping Studies in Science and Technology, Licentiate Thesis, Linköping University, 1998.

[15] Berglund, M., U. Harlin., K. Säfsten, and M. Gustavsson (2011), *Development activities in product introductions – a cross functional approach.* In *Human Factors in Organizational Design and Management –X.* , March 2011, , São Palo, Brazil.

[16] Grote, G., "Uncertainty management at the core of system design," *Annual Reviews in Control,* vol. 28, pp. 267-274, 2004.

[17] Fasth, Å., J. Frohm and J. Stahre, *Relations between Performers/parameters and Level of Automation*. In IFAC workshop on manufacturing modelling, management and control, Budapest, Hungary, 2007.

[18] Fasth, Å., J. Stahre and K. Dencker, *Measuring and analysing Levels of Automation in an assembly system* (2008). In Proc. of the 41st CIRP conference on manufacturing systems Tokyo, Japan.

[19] Fasth, Å. and J. Stahre, (2010). *Concept model towards optimising Levels of Automation (LoA) in assembly systems.* In Proc. of the 3rd CIRP Conference on Assembly Technologies and Systems, Trondheim, Norway.