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Multi-Variant Truck Production - Product Variety and its Impact on Production Quality in Manual Assembly

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Abstract

The trend of diversifying product portfolios increases the challenges for global manufactures to keep production processes robust and maintain high quality. Manufacturing trucks with high level of customization increases the vulnerability to quality deviations in the assembly process. By studying eight manual assembly stations, at a truck manufacturing plant, it was found that high product variety has negative impact on production quality and that high production complexity is connected to high product variety. The study also showed that if operators do not have proper information systems, with accurate data, they need to trust their own knowledge and skills. Results imply that more research is needed to address how the production of products with high variety can be handled to lower the exposure to quality deviations.

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Keywords: Cycle Time, Operations Management, Product Variety, Multi-Serial Production, Production Quality, Percevied Production Complexity

1. Introduction

The competition on the market is intense and companies try to defend their market positions by diversifying their product offerings i.e. mass customization. The amount of customization has a negative effect on productivity [1] and is challenging to the overall manufacturing performance [2]. In an important study of the automotive industry from 1989 [1], the impact of product variety on manufacturing performance has been studied. In that study, it has been found that the amount of customization has a negative effect on productivity. It has also been shown [3] that reducing the amount of option variability in production, the amount of hours spent per product can be decreased. Additionally, scheduling, sequencing and logistics become more complex to handle when the level of product variety is high.

For operators, high product variety increases the complexity exposure and the need for decision support (e.g. instructions) [4,5]. Several studies have investigated the relationship between complexity, quality and cognitive automation, see [6–8]; however, these studies have not focused particularly on the correlation between high product variety and production quality. Even if these studies have been executed in production environments with a high product variety, they have addressed the car manufacturing industry specifically. When it comes to truck manufacturing, the complexity level of the product is higher than in the car manufacturing industry, e.g. wheel base. Even if cars are customized, they are mostly bundled in different packages [3,9]. Such bundling strategies are used to limit product variety in production systems. The production systems for car and truck manufacturing have different preconditions (e.g. short and long cycle times); there is a need to investigate the relation between product variety and production quality in the context of the manufacturing of trucks and other products with similar complexity levels. The study described in this paper, has investigated the relation between product variety and production quality in such a context. To analyse this relation, process planning, cycle time variation and perceived production complexity have been investigated at a case company. Studying process planning and cycle time variation is in this paper used as a method to provide an understanding of the effects of having a high level of product variety in production. In this study, operators' perspectives were

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captured by measuring the perceived production complexity. Such measures contribute to the understanding of how product variety affects the operator work situation which in turn is connected to production quality. In addition, interviews were held with operators, production engineers and a production leader to get a wider view of the production system and its interrelating components. This study is based on production data (planned cycle time and production quality data, questionnaires and interviews). The results from this study contribute to the knowledge of how product variety affects multiple factors that in the end have negative effects on production quality. Such knowledge can be used to better design new production systems.

2. Literature Review and Hypothesis Development

Two hypotheses are developed and connected to the two theoretical frameworks that have been used in this paper. The following two sub sections describe these connections.

2.1. Process Planning and Cycle Time Variation

Line balancing can be defined as 'the method of proportionately distributing workloads within the value stream to meet takt time', where takt time is defined as 'the total work time available (per day or per shift) divided by the demand requirements (per day or per shift) of customers. Takt time establishes the production pace relative to the demand' [10]. This means that the takt time defines the maximum station time to be able to fulfil the demanded quota. More flexibility and capacity in production can be gained by transforming a production line into a mixed-model assembly line. However, the main issue for such a production line is to solve the balancing problem which becomes much more complex [11,12]. As this study reflects upon highly customized trucks, the terminology 'mixed-model assembly line' is defined as *a production line where each product to be assembled is considered unique and consists of different components, features and subsystems*. Since customized products contain high variety of assembled components, the cycle times vary [3] and make it hard to get a good balance between production scheduling and assembly line balancing [13].

Each configured truck, in this study, can be considered as unique. This situation causes the operators at the assembly stations to face a high amount of product variety in terms of differences in work content and cycle times. Therefore, the operators need instructions containing triggers. Such triggers alert the operators to changes in their work tasks and lower the risks of quality issues related to miscommunication [5].

Quality can be interpreted in different ways depending on which stakeholder that is considered. In this paper we define quality as 'all the defined characteristics, parameters, and specifications are within the documented limits' [14]. This means that quality is a measure on how well a product meets the, on beforehand, specified requirements and specifications.

Since the truck manufacturing industry is heavily affected by product variation and production variation we wanted to investigate if this variation can be correlated with production quality, which leads to the following hypothesis:

Hypothesis 1: Production quality is directly related to the amount of possible product variants assembled at assembly work stations.

2.2. Perceived Complexity in Manual Assembly

Integrating product design with manufacturing system design is a way to be more streamlined and competitive [15]. Such integration can be hard to achieve when product variety is high. Such product variety increases complexity. Complexity can be defined as 'the measure of uncertainty in achieving the functional requirements of a system due to poor design or lack of understanding and knowledge about the system' [15]. A complex product is a product that consists of a large number of components and subsystems in which several interconnections and interfaces between components and systems have been designed [16].

Product portfolio complexity is affected by the lack of relevant information for decision-making during the product design phase [17]. Furthermore, information and knowledge gaps tend to influence the amount of new parts and components in a product portfolio. An enlarged amount of such parts and components contribute to an increase in product complexity which negatively influences production performance and quality as the products become harder to handle in the production infrastructure [17]. To control the complexity flow in the production system, proper assembly line sequence planning can be used. [18]. From previous studies (e.g. [7,8,19]), complex assembly tasks have been shown to cause costly assembly errors in manual assembly work. It has also been shown that there is a direct correlation between complexity and assembly time (cycle time) [8]. To be able to minimize complexity in manual assembly, measurements can be used to identify what is considered complex and how it can be addressed [20]. There are several methods available for measuring complexity in a production environment, see [21]. Those methods are objective and based on analysis of extensive amounts of production system data; however, such data is not always available.

When comparing the car manufacturing industry with the truck manufacturing industry one can realize that there are major distinctions between them. The product complexity is very different when comparing a car with a truck. Such a difference is very evident in terms of vehicle configuration (e.g. wheel base). Since trucks are much more complex than cars, complexity phenomena proven in the automobile context are hypothesized to be even more evident in the trucks manufacturing context. The following hypothesis is defined:

Hypothesis 2: High product variety increases the level of production complexity which affects the operator.

3. Research Methodology

A mixed method approach combining qualitative and quantitative measures was used. By combining both qualitative and quantitative data collecting methods, there are larger opportunities for good understanding of the phenomenon studied [22]. The chosen research design was based on the explanatory sequential design [22,23] where the study began with a quantitative data collection and an analysis followed by a qualitative data collection and an analysis.

The first step in this study was to measure the variation of cycle times at the chosen assembly stations. The cycle time data was collected from one of the company's production information systems for a sample of 37 production days. As a second step, the recorded production quality data for the same sample was studied. The third step was to measure operator perceived complexity by using the 'CompleXity Index' method, which was based on a standardized questionnaire [21]. As a final step, semi-structured interviews were held with involved operators, production engineers and the responsible production leader. The reason for choosing semi-structured interviews was that the amount of operators in this study was limited and the interview form made it possible to collect unexpected but very relevant data [24].

The factory studied manufactured 14 385 heavy duty trucks in 2014. The production volume for this factory is 60 manufactured trucks per shift on a single mixed-model assembly line. For this study, a total of eight pre-assembly stations were selected with the purpose of studying assembly stations with considered low respectively high variation in terms of both cycle times and product configurations. Fig. 1 shows the selected stations. In six of the stations, bogie crossbeam members (1-6) are assembled and engine beams (7) and front beams (8) are assembled at the following two stations.

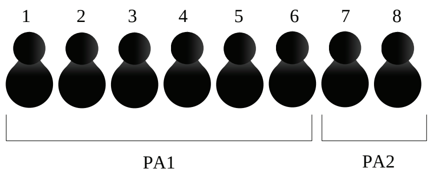

Fig. 1 The setup of the pre-assembly areas investigated in this study.

The stations contain both assembly work and kitting. In total, 9 operators are operating these stations. The six bogie crossbeam stations belong to one production area, PA1, while the engine and front crossbeam member stations belong to a second production area, PA2. The production sample for this study consists of 2034 trucks manufactured during 2015 with a valid takt time of 8.49 minutes (509 seconds).

4. Results and Analysis

Four different kinds of data have been collected during this study; cycle times, quality data, perceived complexity and interview data. The following sections present the main findings together with an analysis of the data.

4.1. Deviation in cycle time between product variants

The cycle times for the 2034 manufactured trucks used as a sample in this study, were collected from the production system of the company. Average cycle times based on the sample are shown in Table 1.

Table 1: Average cycle times in seconds per station based on the chosen sample.

Station	Min	Mean	Max	Std. Deviation
Kitting	297	375	529	± 48
Cable mat	22	465	520	± 42
Cabling	165	295	662	± 93
Valve/Tank	155	325	617	± 115
Air tanks	0	154	577	± 145
Bogie valves	166	454	658	± 119
Engine	437	346	468	± 8
Front	268	445	470	± 60

The assembled trucks are customized and some configurations contain more work content at an assembly station than others. The air tank station is such a station where only trucks with certain configurations are assembled. This leads to relatively low min and mean value for the air tanks station and a high standard deviation, which can be seen in Table 1. In this sample, only 43 % of the trucks had work content to be carried out at this station. When no work is to be carried out at this station, the operator is working at another station with similar setup. The cycle times were found to have high standard deviation for cabling, valve/tank, air tanks and bogie valves, which indicated large spread of cycle times in the sample compared to the other stations. Fig. 2 visualizes the cycle time distribution for the stations studied, where the cycle times are organized by station and sorted from low to high values. As seen in Table 1, at the kitting, cable mat, engine and front beam stations, the cycle time variation was in a much narrower span compared to the other sample stations. This would suggest that half of the stations are less affected during line balancing in terms of available assembly time. Additionally, for the stations with wider cycle time variation, there were more truck configurations in the sample that exceeded the available assembly time compared to the other stations in the sample. The addressed cycle time variation is supported by the result from interviews with assembly operators who stated that the assembly work is stressful due to the amount of work to be carried out within the available assembly time.

The collected cycle time data corresponds to unique truck configurations and orders assembled at the sample stations. Each assembled truck has a calculated cycle time for each station in the assembly line and pre assembly stations. Therefore, a specific cycle time can be addressed to a specific product variant; however, during interviews it was emphasized that there are also truck configurations that share the same cycle times as other configurations. An example of such circumstances is the positioning of specific components which affects the assembly operation, but not the cycle time itself. Therefore, the amount of different cycle times shown in Table 1 represents an absolute minimum amount of product variants at the sample stations. In fact, there is an even larger amount of product variants than these diagrams illustrate.

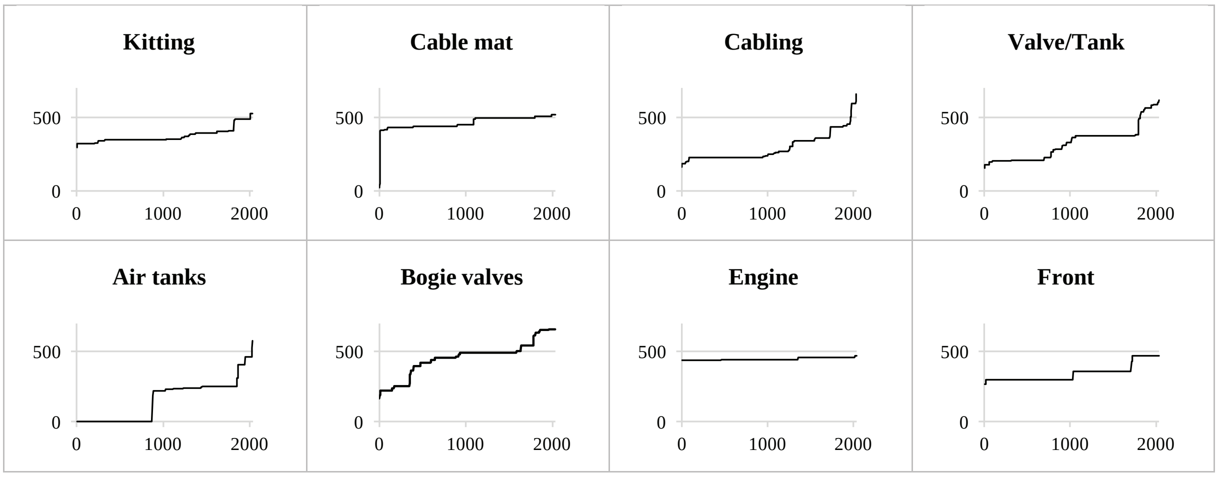

Fig. 2. The distribution of cycle times, given in seconds, is organized by station and sorted from low to high values.

The valid cycle times for the truck sample at the bogie valve station with the correct production sequence are shown as an example in Fig. 3. This compilation of cycle times illustrates the intensity difference in work content which is connected to the amount of possible product variants. The interviewed operators indicated that they do not perceive their assembly work as difficult, but mentioned that it is stressful to accomplish all given assembly tasks within available assembly time. This view was also supported by the production leader.

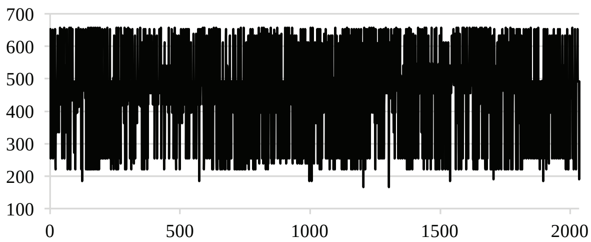

Fig. 3. The cycle times in seconds for the bogie valves station sorted in actual production sequence.

4.2. Perceived complexity in Manual Assembly

CompleXity Index, CXI [21,25], is a method for measuring perceived complexity at a work station, by using a standardized questionnaire. This questionnaire does not only provide statistical data, the questions themselves also contribute to the understanding of how perceived complexity can be negatively affected. In this case, the questionnaire was filled in by 14 operators. The result shown in Table 2 is ranked using three categories and colours; low complexity is marked green for CXI < 2; moderate complexity is marked yellow for 2 ≤ CXI < 3.5; high complexity is marked red for CXI ≥ 3.5.

Table 2: The result from the assessment of perceived complexity at seven out of the eight stations in the sample is presented in this table.

STATION	Kit	Cable mat	Valve/ Tank	Air tanks	Bogie valves	Engine	Front
Station design	3.3	3	2,8	3	4	3.2	2
Work variance	4.7	4.5	4	5	3	3.8	4
Disturbances	1.7	1.8	4,3	4.5	4	3.3	4
Total CXI:	**4.5**	**4.1**	**4.3**	**4.9**	**5**	**4.5**	**5**

The CXI measures as seen in Table 2 only show values for seven out of eight stations. The cable mat station and the cabling station are merged together and the two operators work on both the stations. Therefore, no measures were conducted on the cabling station. The result suggested that all the sample stations are considered to have high perceived complexity. The second area, *work variance*, was found to contribute the most to the high perceived complexity. A majority of the operators agreed on the fact that their production areas are handling large amounts of product variety and variants that are uncommon. This view was also supported by the interviews with operators, production engineers and the production leader.

The interviewed operators stated that they do not have sufficient time to read available assembly work instructions. The main reason is that they find it hard to locate and detect needed data in the assembly work instructions. Instead, the operators often trust their own experience and base their decisions on skills. It was suggested that pictures in the assembly work instructions can replace text, but the operators stated that it would not be possible to have that due to the high amount of product variants and the constant need for updating assembly work instructions. Furthermore, it was stated by the operators and also supported by one of the production engineers and the production leader that distributed assembly work instructions are not always correct in terms of details specifics.

4.3. Quality

Considering quality, the interviewed operators mentioned that quality feedback is not always provided and therefore does not provide prerequisites for working with continuous improvements. When a deviation is detected, a deviation card is filled in and later registered in the quality deviation system. Sometimes, the level of details in the deviation card is not sufficient to be able to register it in the follow up system. This leads to that not all quality deviations are reported. The production engineers and the production leader mentioned that assembly errors are common, but often corrected before the product leaves the production area.

In the quality follow up system, production quality data is broken down to production areas (PAs) and not to a station level. Therefore, the recorded production quality data for this study has also captured stations belonging to the same PA:s as the sample stations. In total, 1384 errors were recorded for the truck sample for PA1 (489) and PA2 (895). Four categories were used to classify different quality deviations; assembly errors, damage on part, logistic errors and product errors. Both at PA1 and PA2, the majority of the quality deviations were addressed to assembly errors, 64 % respectively 65 %.

During the interviews, it was stated by the production leader, the production engineers and the operators that the amount of product variety is related to the level of production quality. One of the production engineers stated that the amounts of well-known truck configurations are only a smaller part of the amount of trucks that are assembled in the factory each day. Additionally, the interviewees stated that errors in assembly work instructions make their work more difficult. One example which was given by one of the production engineers was screw lengths. Sometimes, too short screw lengths are specified in the assembly work instructions.

5. Discussion

During the first part of the study, the cycle times from the production sample were collected and analysed. The production sequence was organized in such a way that work intensive truck configurations did not follow each other along the production line. This is exemplified in Fig. 3 where the cycle times dramatically vary for each truck. However, truck configurations with low work content can still have high intensity at certain assembly stations. The main reason for this is the spread of product variety that is treated in this particular factory. In fact, the factory studied, has the highest product variety and the most difficult ones, than in the entire GPN. Product variety is normally handled by optimization; however, such optimization problems are hard to solve when product variety is at its extremes.

When it comes to product variants and quality, several interesting factors appeared in the study; the amount of product variants, operator experience and knowledge, line balancing, assembly work instructions, cycle time, delays in part delivery, stress etc. During the interviews it was expressed by operators, production engineers and the production leader that these factors need more attention.

It was evident from all interviews that available assembly work instructions have improvement potential. As stated in [5], assembly work instructions should be structured in such a way that they contain triggers which make it easier for the operator to detect and collect needed and relevant information. As the sample stations contain much cabling and positioning activities, decision support such as drawings and pictures are needed, but are not provided. As mentioned earlier, the operators do not always read supplied assembly work instructions. Most often the operations are correctly carried out; but, as mentioned by the production leader and the production engineers, the operators sometimes fail to recall a specific truck configuration and work content, which causes quality deviations.

As long as assembly work instructions are not improved in terms of simplification and correctness, there is a low chance that an increase in the use of assembly work instructions will occur. Together with other mentioned factors it is evident that the *amount of product variants is directly connected with production quality*.

The level of perceived complexity was found to be high for all sample stations. The main contribution to this perceived complexity is high work variance. The way of handling product variants is affecting the operators and other functions involved in the production process. The amount of work content on the stations is very dependent on what truck configurations that are ordered and the setup of the manufacturing process itself. Both the perceived complexity measures and interviews indicated that operators in general are experiencing stress in their work. This was directly addressed to cycle times and available assembly time.

The engine and front beam member stations were in the beginning considered to have lower level of work variance compared with the bogie stations. However, as presented in Table 2, both stations are considered to have high level of perceived complexity. The main contribution for the high perceived complexity level is as for the total sample, work variance and competence. A reason for this commonality in complexity was not given, but the result suggested that current work variance is affecting operators' perception of their work situation more than expected at the beginning of this study.

All factors previously discussed, are related to production complexity. In Fig. 4 the connection between product variety, production complexity and production quality is illustrated. In this study it is argued that product variety affects several factors in the operational context. High product variety affects cycle times and the line balancing optimization. High product variety makes assembly work instructions more vulnerable to content errors. Moreover, the high product variety makes it harder to make assembly work instructions optimally fit every assembly activity. These sources have been in focus for this study and *have shown to influence production complexity negatively*, which in turn affects both the operator and the production quality. The high product variety increases the number of potential sources for deviations and errors. These sources of errors negatively influence production quality.

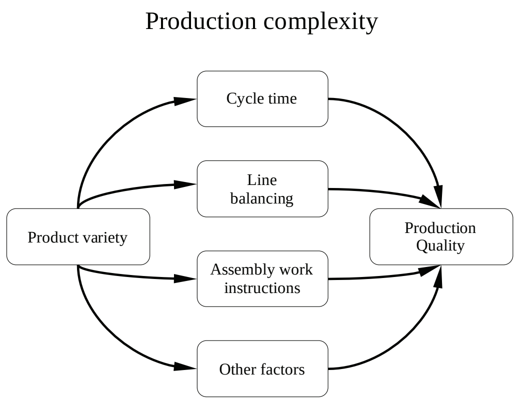

Fig. 4. Product variety makes production complex. Several factors are considered to affect operator performance.

5.1. Future Research

This study has shown that the amount of product variety is connected to the level of perceived complexity and production quality. Future research should focus on how production systems can be better designed to support operators in the assembly process. Furthermore, future research should focus on how a production system can be better designed to handle high product variety. During the study it was also found that there is room for improvements in terms of handling quality deviations efficiently.

6. Conclusion

Managing high levels of product variety in manual assembly is challenging in terms of line balancing, productivity and production quality. An assembly environment with high product variety tends to increase operators' perceived complexity. This perceived complexity contains several factors that need attention to assure production with the highest production quality possible.

This study has shown the importance of having a good assembly information system support for the operators, especially when facing high product variety. Products with high variety make line balancing more challenging in terms of high cycle time variation. A variation in work content makes the production sequence sensitive to production disturbances and makes it harder to increase utilization. This study has shown the difficultness to design and create robust production systems when manufacturing products with high variety.

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