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Effective relationships of factors in a manual assembly line environment

Jaakko Peltokorpi*

Engineering Design and Production Department,
Aalto University School of Engineering,
P.O. Box 14200,
Aalto 00076, Finland
E-mail: jaakko.peltokorpi@aalto.fi
*Corresponding author

Mika Lohtander

LUT Mechanical Engineering,
Lappeenranta University of Technology,
P.O. Box 20 FI-53851 Lappeenranta, Finland
E-mail: mika.lohtander@lut.fi

Sampsa V.A. Laakso

Engineering Design and Production Department,
Aalto University School of Engineering,
P.O. Box 14200,
Aalto 00076, Finland
E-mail: sampsa.laakso@aalto.fi

Abstract: A manual assembly line environment includes a large number of factors that affect the performance of the system. At the moment, these factors and their effects are investigated in separate research papers that relate to different disciplines, and thus there is an increasing need to handle them together. This study contributes to the understanding of these factors and their relationships from both an operations and a human perspective. The factors are examined in the case of a mixed-model assembly line in which process design and agile responses to variation are the key features in terms of performance. The information on the relevant factors and their effects is primarily based on the literature. The study shows that a network analysis method can be used to present this information in a more visual and understandable form to show the importance, connections, and commonality of factors.

Keywords: manual assembly; assembly line; mixed model; complexity; effective relationships; factors; operations; human resources; management; network analysis method; performance.

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Biographical notes: Jaakko Peltokorpi is a Doctoral Candidate and Assistant in Engineering Design and Production Department at Aalto University School of Engineering, Finland. His research interests focus on the efficiency and productivity issues concerning flexible worker coordination in manual assembly systems. He has a Master's Degree in Production Engineering.

Mika Lohtander is a PhD (Tech) and Researcher in LUT Mechanical Engineering at Lappeenranta University of Technology, Finland. His Dissertation is entitled 'On the development of object functions and restrictions for shapes made with a turret punch press'.

Sampsa V.A. Laakso is a Doctoral Candidate and Assistant in Engineering Design and Production Department at Aalto University School of Engineering, Finland. He is interested in finite element simulation of cutting. He has a Master's Degree in Production Engineering.

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1 Introduction

The final assembly is a crucial part of a manufacturing chain, especially from the costing point of view. Approximately 30% of manufacturing workers are involved with assembly tasks and 25–50% of the total cost is related to assembly (Mattsson, 2013).

Assembly systems in industry are complex because of the wide product variety. The main reason for this product variety at the moment is mass customisation. Mass customisation is a strategy for delivering individualised products at the same price as mass products (Zhu et al., 2008). Furthermore, mass customisation forces the assembly system to handle high flexibility, small batch sizes, low product volume and a large number of variants (Heilala and Voho, 2001) with low costs (Schleich et al., 2007). Assembly systems also play a role in social sustainability, which makes it important for production companies to be attractive to a workforce with varying ages, skills and health issues. Therefore it is possible to say that increasing complexity is one of the main challenges in today's manufacturing (Mattsson, 2013).

The complexity of assembling affects performance in terms of quality, productivity (Zhu et al., 2008), reliability and production time (Mattsson, 2013). As final assembly work is often carried out manually or is partly automated, the role of humans is increasingly important, e.g. bad choices are connected with high costs or becoming exhausted is connected with variable reliability (Mattsson, 2013). Therefore, though manual assembly needs skilled labour, the design and management of such production should be carried out in such a way that they foster the long-term performance of labour and further the competitiveness of operations.

In practice, operations and human resources are closely related to each other. Therefore, instead of handling operations- and human-related matters separately, the managers in both fields should know the value of working with both of them together (Boudreau et al., 2003). This separation is also shown in the academic world since,

e.g., relatively few publications consider both the operational and human effects of operations system design in manufacturing (Neumann and Dul, 2010). In any case, it is necessary that operations- and human-related factors are increasingly investigated together in order to gain a better understanding of their importance and mutual relationships in terms of system performance. Although, at the moment, a relationship may be known, a lack of detailed information can restrict the selection of factors for investigation (Larco Martinelli, 2010). Thus, in order for there to be a more extensive investigation of the relevant factors, the ability to provide detailed descriptions of their relationships should no longer be significant. This also facilitates the investigation of factors and relationships from both operations and human-related research fields. Finally, an analytical method that can present the information on relationships in a more understandable form should be used.

The ultimate goal of this study is to increase the understanding of the nature of human-assembly line combination. To do this, the present study examines the relationships of operations- and human-related factors in the case of a manual mixed-model assembly line. In such a line model, several different variations of the same base product are assembled on a single line (Boysen et al., 2008). The relevant factors are selected on the basis of the nature and performance-critical matters of the system in question. The information on the factors and their mutual effects is primarily based on the literature. This information is imported into the Gephi software suite (Bastian et al., 2009) to analyse the importance, connections and commonality of the factors by means of a relationship network.

This paper expands the earlier study of the present authors (Peltokorpi et al., 2013). The paper is structured as follows. Next, Section 2 presents the relevant studies that provide the basis and show the need for the investigation this paper represents. Then, Section 3 presents the background and the model to examine in more detail the assembly line environment and defines the factors and effects to be examined. Section 4 justifies the analytical method to be used and shows and analyses the results generated by the network analysis software. Finally, Section 5 discusses the results, followed by the conclusions and further research in Section 6.

2 Towards the integration of operations- and human-related factors

First, this section introduces the aspects of the performance of the system the present study investigates. Secondly, the previous papers that are most relevant to the integration of operations- and human-related factors and which act as a basis for the investigation in this study are reviewed.

A manual assembly system is a system in which both the design of value-creating operations and skilled workers, through performing those operations, play a key role. A company that is capable of highly performing production sets successive targets and manages the complex system from both an operations and a human resources perspective. This management also means agile decisions to respond to changing situations in production. Companies achieving such an operational regime typically set targets such as reducing work-in-process (WIP), increasing throughput, and maintaining a minimum product cycle time or good job satisfaction (Hopp and Van Oyen, 2004). However, the interface between the policies achieving, e.g., maintaining the minimum cycle time and good job satisfaction should be understood since Boudreau et al. (2003, p.196) state that

“operations management (OM) policies can only be carried out by people and human resources management (HRM) policies are effective only if they foster people doing organisation-critical tasks”. Their study points out the potential in terms of the capability and understanding of the interface between OM and HRM. At the same time they note that, e.g., authors in the research fields of both OM and HRM mostly handle these different management aspects as separate subjects in separate communities of scholars.

Rather than HRM, Neumann and Dul (2010) investigated the separation of human factors (HF) from OM. According to them (Neumann and Dul, 2010, p.924), the difference between HRM and HF is that “HRM focuses more on selecting and developing people in order to fit them to the system, whereas HF focuses on adapting the system design in order to fit it to the people”. The study made an extensive search with suitable search terms for scientific papers in both business and human factors databases. Only 45 empirical studies were identified in which both the operations and human effects of operations system (OS) design in manufacturing were studied. 95% of those papers that were identified suggested that the “application of HF in OS’s can support improvements on both human and system outcomes” (Neumann and Dul, 2010, p.941).

A response to the call of Boudreau et al. (2003) was contributed by the dissertation of Larco Martinelli (2010), which incorporated relevant worker-related factors into the operations management (OM) models. In the study, the OM models that are examined cover different types of models, such as layout, scheduling or work-flow models. More specifically, e.g., the work-flow models cover categories such as the control of WIP and worker assignment and work-sharing policies. According to the study, these OM models aim to optimise the performance of traditional operational measures such as maximising throughput and line efficiency or minimising staffing costs and lateness of delivery. Furthermore, the decision variables of OM models can be directly related to individual performance factors. The study found that the link between certain human-related factors (e.g., learning and forgetting, goal setting and peer pressure) and individual performance can be described mathematically, though with certain limitations. On the other hand, some of the factors affecting performance (e.g., incentives, fatigue, feedback and effort evaluations of workers) were known, but in insufficient detail for it to be possible to transfer them into a mathematical description. The study laid down criteria for selecting human factors for examination, e.g., according to their impact on the feasibility or optimality of OM models. This also helped to reduce the number of human factors to be modelled.

The present study continues the research framework introduced in the above-mentioned studies, specifically by studying relevant operations- and worker-related factors in the context of a manual assembly line. In relation to the study of Larco Martinelli (2010), the ability to provide mathematical descriptions of the relationships between the factors is no longer significant since, in the present study, only information (reviewed from the literature or based on the opinion of the present authors) about a mutual effect between the factors is needed. This also makes the criteria for selecting human-related factors (as well as operations-related factors) for examination less rigorous.

3 Integration of operations- and human-related factors in a manual assembly line environment

This section first presents the background for studying the assembly environment in question. Secondly, aspects provided by Larco Martinelli (2010) for studying factors in such a human-centred environment are reviewed. Thirdly, the model (framework) for proposing factors and effects and the principles used for selecting them for investigation in the environment under study are presented. Fourthly, the information is presented in terms of definitions of the factors and their effects.

3.1 Background and aspects for studying a manual assembly line environment

Initially, the idea for the authors studying the relationships of factors in a manual assembly line environment arose through reviewing previous studies of manual assembly systems. It was found that operational factors affect human-related factors and vice versa; for example, cycle (takt) time affects job satisfaction and the pace of processing (Jürgens, 1997), product variety affects labour productivity (MacDuffie et al., 1996) and learning and forgetting affect line productivity (Shafer et al., 2001). It was also found that in today's agile companies, workforce flexibility in terms of worker cross-training and coordination plays a key role (Hopp and Van Oyen, 2004). One of the studies found concludes that complexity of assembly tasks affects operation costs, but the importance of complexity factors on these costs needs further research (Falck et al., 2012).

Although numerous papers mention the mutual effects between many relevant operations- and human-related factors, to the best of our knowledge, a broader investigation in which several factors and their relationships are handled together is still lacking. Regarding the effects of factors, Larco Martinelli (2010) suggests relating decision (operational) variables (factors) to individual performance through intermediate factors if there are at least two operational variables and at least two individual performance factors under consideration. This principle of setting intermediate factors is relevant for use in the model in the present study. When relevant factors are being considered, the following recommendations given by Larco Martinelli (2010) can also be seen as valuable in the present study:

- when incorporating skill levels one should consider the aspects of, for example, mathematically described learning and forgetting processes, as well as factors that affect learning and skill rates (besides experience) that can be affected by operational variables such as task complexity and training periods
- when modelling a specific motivational driver one should use specialised theories of motivation that may directly address that driver
- when objectives related to job satisfaction are being incorporated, only a single (or very few) relevant aspects of job satisfaction should be explicitly modelled as an objective(s).

Regarding models for analysing the relationships between operations and human-related factors, the two following points from Larco Martinelli (2010) are also valuable:

- the OM models that are formulated should be robust enough to take changes in empirically defined relationships between human factors and operations into account

- an analytical model using information from an empirical research study can assess the commonality between the factors affecting operational performance and well-being.

3.2 Assembly system environment and model under study

In this paper, a *mixed-model assembly line* environment is studied. In such an assembly line design several different variations on the same base product are assembled on a single line (Boysen et al., 2008). The products are supposed to be physically such that they can be processed and handled by a single worker. The customisation of products contributes to variation in processing times, which further appears as an imbalance in the workload between the stations. This imbalance can be responded to not only by maintaining buffer storage between the stations but also by enabling one worker to help another in their work.

The performance of a manual assembly system is essentially based on the targets set and on the policies used, not only from the operations point of view but also from that of human resources, as discussed in the previous section. To make an equal examination of the relationships of factors concerning both operations and individual workers, the selection of the ways in which the factors and their connections are presented has to be carefully considered. In the model in Figure 1 the factors are presented as a linear process; the effects of the factors, however, can be multi-directional. Moreover, although a manual assembly line is dynamic in nature the mutual effects between the factors are assumed to be valid all the time, and thus the model is assumed to be static. In the figure, the operations-related factors are shown against a dark grey background and the human-related factors are shown against a light grey background.

The selection of the factors through this parallel linear process in Figure 1 is based on the following three principles:

- the factors are relevant enough to represent the environment the present study examines
- the factors (on a conceptual level) are known or applicable on the basis of the literature
- the factors represent operations- and human-related factors equally.

In defining the factors, the most relevant definitions from the available have been selected. The definitions of operations-related factors under study were found in the books, for example, or were generally known to the present authors. The consideration of human-related factors naturally required papers from outside the production and operations management research fields to be reviewed. In this case, more attention has been paid to the most original papers. Many relevant definitions were also selected based on the information in the dictionaries. The mutual effect between the factors is selected for inclusion in the model if it is mentioned in the literature or at least if it was thought to exist on the basis of the opinion of the present authors.

The target factors for the end of the linear process in Figure 1 are set as *production costs* for the operations point of view and *tenure length* for that of an individual worker. When the target factors have been set, one might study the preceding factors step by step. Such an examination of factors and connections, however, easily leads to difficulties in

selecting and omitting the factors and finally to an excessive number of factors that cannot be handled systematically. Therefore, this study also sets the base factors as being in parallel at the beginning of the linear process. This study is interested in *system base characteristics* as operations-related factors and *worker base characteristics* as human-related factors.

In the model, an arrow between the factors simply indicates that one factor affects another. An effect most commonly occurs towards the end of the process. In addition, an effect can occur on the same level of the process or towards the beginning of the process. The most interesting feature is that a connection may occur from an operations- to a human-related factor or vice versa. Instead of presenting any numerical values or even positive or negative impact between the factors, the model in Figure 1 only indicates whether an effect between the factors is known or, at least, if it can be thought to exist. Different levels of the factors in the process are selected on the basis of their relevance to the environment being examined and on their ability to support the parallel handling of both types of factors.

Figure 1 A process model for the selected factors and their effects

3.3 Definitions of factors

The definitions of operations- and human-related factors on different levels of the process model in Figure 1 are presented.

System base characteristics

- *available capacity* (fixed): available time for production in a period (of one day) (Chambers and Johnston, 2009)

- *demand* (fixed): demand at capacity as number of products to be processed in a period (of one day) (Chambers and Johnston, 2009)
- *total work content*: predetermined average total time for completing all the required tasks in a system
- *number of tasks*: number of tasks (stations) in a system
- *number of workers*: total number of workers in a system.

Worker base characteristics

The base characteristics of an individual worker are classified as performance, social and mental characteristics, as in the study of Yaakob and Kawata (1999). The relevant factors from these characteristics are selected and defined as follows:

- *job-related experience*: previous experience influencing the current job of a worker
- *professional knowledge*: activity-oriented knowledge (information about facts or proven methods for problem solving and information which is needed to define and understand problems that are faced) in one's professional area (Bromme and Tillema, 1995)
- *cooperation skills*: skills in "the action of working or acting together for a common purpose or benefit"¹
- *sense of responsibility*: awareness of one's obligations²
- *self-confidence*: belief in one's abilities to produce results (Schunk, 1991).

Task characteristics

- *percentage of machine-paced work*: shares of tasks in which machines are pacing labour at work (Yelle, 1979)
- *learning rate*: computational speed of the decrease in the average time for completing a task when task completions are doubled (on the basis of Wright's learning curve) (Yelle, 1979)
- *task variety*: degree of variety of a task at a single station as a result of the customisation of products
- *takt time*: given maximum time to complete a task in order to meet the demand.

Task-related competence of worker

- *task cooperation efficiency*: level of efficiency in the cooperation of two workers on a shared task
- *task-related skills*: task-related "special competence in performance"³
- *job autonomy and responsibility*: increased worker discretion and independence related to the ways work is done (Hackman et al., 1975) and being given responsibility for work
- *self-efficacy*: the expectation or belief that one can successfully complete a task (Bandura, 1977).

Task performance

- *deviation of task time from standard*: deviation of task completion time from takt time
- *task completion time*: the elapsed time to complete a task

Worker performance

- *processing rate*: number of completed items per time unit (Chambers and Johnston, 2009)
- *learning and forgetting*: “the act, process or experience of gaining knowledge or skill”⁴ and “lack of skill retention” (Nembhard and Osothsliip, 2001).

System performance

- *cycle time*: the average time a job spends within the system being processed plus waiting in a (WIP) queue (Curry and Feldman, 2011)
- *throughput*: the number of completed jobs leaving the system in a unit of time (Curry and Feldman, 2011)
- *idle time*: the time during which a worker cannot work as a result of starving or blocking (Zavadlav et al., 1996)
- *amount of WIP*: average total number of jobs within a system that are either being processed or waiting in a queue for processing (Curry and Feldman, 2011).

Worker outcome

- *job satisfaction*: “the extent to which a person’s hopes, desires, and expectations about the employment he is engaged in are fulfilled”⁵
- *work motivation*: the work-related “psychological force that moves a person to act to meet a need or achieve a goal”⁶
- *experience of success or failure*: the extent to which a worker experiences success or failure at work.

System response

- *cross-training or training*: “enabling workers to perform multiple task types” (Hopp and Van Oyen, 2004, p.3) or training new workers in a task
- *task cooperation*: sharing the same task with another worker
- *labour turnover*: the number of workers employed by a company during a given period to replace workers who have left.⁷

Worker response

- *worker resignation or dismissal*: a worker leaves or is dismissed from a job
- *job enrichment*: providing a worker with a “range of tasks and challenges of varying difficulties”⁸
- *absenteeism*: “habitual absence from work”.⁹

Operations target and worker target

- *production costs*: all the costs resulted from maintaining the present assembly production
- *tenure length*: the length of time a worker has held his current job position.

Table 1 presents the effects between the factors (effect from factor located in the column on the left and effect on factor located in the middle column). Information source column on the right shows whether the effect is based on the literature or authors' assumption. A text inside the parenthesis after certain factors specifies the original source or assumption in question.

Table 1 Effects between the factors

<i>Effect from</i>	<i>Effect on</i>	<i>Information source</i>
Available capacity	Takt time	Chambers and Johnston (2009)
Demand	Takt time	Chambers and Johnston (2009)
Total work content	Number of tasks (stations)	Heizer and Render (2006)
Number of tasks	Number of workers	It is assumed
Number of workers (size of work unit)	Job satisfaction	Porter and Steers (1973)
Number of workers	Production costs	It is assumed
Job-related experience	Task-related skills	Quinones et al. (1995)
	Professional knowledge	It is assumed
Professional knowledge	Task-related skills	Boudreau et al. (2003)
Cooperation skills	Task cooperation efficiency	It is assumed
Sense of responsibility	Cooperation skills	It is assumed
	Job autonomy and responsibility	It is assumed
Self-confidence	Self-efficacy	Schunk (1991)
Percentage of machine-paced work	Learning rate	Yelle (1979)
Learning rate (level of task difficulty)	Self-efficacy	Bandura (1977)
Learning rate	Learning	Yelle (1979)
Task variety	Forgetting (learning loss)	Yelle (1979)
Task variety (skill variety)	Work motivation	Hackman et al. (1975)
Takt time (cycle time)	Number of tasks (stations)	Heizer and Render (2006)
	Job satisfaction	Jürgens (1997)
	Processing rate (pace)	Jürgens (1997)
Takt time (standard time)	Learning	Yelle (1979)
Takt time	Deviation of task time from standard	It is assumed

Table 1 Effects between the factors (continued)

<i>Effect from</i>	<i>Effect on</i>	<i>Information source</i>
Task cooperation efficiency	Processing rate	It is assumed
Task-related skills	Processing rate	It is assumed
	Task cooperation efficiency	It is assumed
	Job autonomy and responsibility	It is assumed
	Learning	Yelle (1979)
	Self-efficacy	Bandura (1977)
Job autonomy	Job satisfaction	Hackman et al. (1975)
	Work motivation	Hackman et al. (1975)
Job responsibility (as a sense)	Job satisfaction	Herzberg (1968)
Self-efficacy	Work motivation	Bandura (1977)
	Processing rate (performance)	Bandura (1977)
	Cooperation skills	It is assumed, Bandura (1994)
	Job autonomy and responsibility	It is assumed
	Self-confidence	It is assumed, Bandura (1977)
Deviation of task time from standard (imbalance)	Idle time (starving)	Zavadlav et al. (1996)
	Amount of WIP	Bukchin et al. (2002)
Deviation of task time from standard (performance)	Job satisfaction	Judge et al. (2001)
	(through Experience of success or failure)	It is assumed
Task completion time	Cycle time	Curry and Feldman (2011)
	Deviation of task time from standard	It is assumed
Processing rate	Task completion time	It is assumed
Learning	Task-related skills	Yelle (1979)
Forgetting	Task-related skills	Nembhard and Osothsip (2001)
Learning and forgetting	Experience of success or failure	It is assumed
Cycle time	Throughput	Little (1961)
Throughput	Production costs	It is assumed
Idle time	Production costs	It is assumed
	Task cooperation	It is assumed
Amount of WIP	Work motivation	It is assumed, Bandura (1977)
	Idle time (blocking)	Zavadlav et al. (1996)
	Production costs	It is assumed
	Throughput	Little (1961)
	Cycle time	Curry and Feldman (2011)

Table 1 Effects between the factors (continued)

<i>Effect from</i>	<i>Effect on</i>	<i>Information source</i>
Job satisfaction	Cooperation skills	It is assumed
	Processing rate (performance)	Judge et al. (2001)
	Absenteeism	Porter and Steers (1973)
	Labour turnover	Porter and Steers (1973)
	(through worker resignation)	It is assumed
	Job enrichment	Herzberg (1968)
Work motivation	Work motivation	It is assumed
	Job enrichment	Herzberg (1968)
	Self-efficacy	It is assumed, Bandura (1977)
	Job satisfaction	It is assumed
	Absenteeism	Nicholson (1977)
Experience of success or failure	Cross-training	It is assumed
	Self-efficacy	Bandura (1977)
Experience of success or failure (sense of achievement)	Job satisfaction	Herzberg (1968)
Cross-training or training	Learning and forgetting	Nembhard and Osothsliip (2001)
	Production costs	it is assumed
Cross-training	Work motivation	Hackman et al. (1975)
	Job satisfaction	Hackman et al. (1975)
	Worker resignation	Becker (1962)
	Task cooperation	It is assumed
Task cooperation	Learning and forgetting	It is assumed
	Idle time	It is assumed
	Task cooperation efficiency (productivity)	Hanna et al. (2007)
Labour turnover	Production costs	It is assumed
	Training	It is assumed
Worker resignation or dismissal	Labour turnover	It is assumed
	Tenure length	It is assumed
	Number of workers	It is assumed
Job enrichment	Work motivation	Hackman et al. (1975)
	Job satisfaction	Hackman et al. (1975)
	Job autonomy	Hackman et al. (1975)
	Cross-training	It is assumed

Table 1 Effects between the factors (continued)

<i>Effect from</i>	<i>Effect on</i>	<i>Information source</i>
Absenteeism	Worker resignation or dismissal	It is assumed
	Production costs	It is assumed
Production costs	Worker dismissal	It is assumed
Tenure length	Work motivation	It is assumed, Globerson and Crossman (1976)
	Job satisfaction	
	Professional knowledge	It is assumed, Quiñones et al. (1995)

4 Network analysis for understanding relationships between factors

In this section, first, different methods for analysing the relationships between the factors are reviewed. Secondly, the advantage of the network analysis method over other methods is justified. Thirdly, the steps involved in using that method to get the results are presented.

4.1 Selection of analytical method

The information on factors and connections presented in Figure 1 needs a suitable analytical method to increase the understanding of the relationships between the factors in the environment under study. First, it is essential that the selected method is able to handle cause-effect relationships, especially those involving multiple factors. There are methods for that, such as association rules (Agrawal et al., 1993), but they typically do not consider sequences of multiple variables, a matter that is also significant in this study. One method for handling sequences of relationships is, e.g., causal networks, as presented in Pearl (2000). A method to investigate statistical dependency (but does not necessarily deal with causality) between the factors is correlation analysis, which measures strength as an association between two variables (Archdeacon, 1994). Correlation can be further used to construct clusters (communities) of several variables (Hartigan, 1972).

As none of the methods presented above would be able to analyse causality, commonality and the centrality of factors at the same time, a more comprehensive method had to be found. Such a method is network analysis, which is represented by, for example, the Gephi software, as presented in the paper by Bastian et al. (2009). That paper states that the usefulness of a network analysis is based on the information at nodes (factors) and at the edges (effects). The Gephi software has been used for some special research purposes, such as to show the ways in which co-creation occurs through financial linkages, to characterise the proximity and dependency of technological areas, and to analyse problematic enterprise-scale information systems.¹⁰ A network analysis of the relationships between factors similar to those in the present study was performed by Laakso et al. (2013), who examined the interdependencies of metal-cutting parameters. On the basis of the principles of the networks analysis method (Gephi) and the research purposes it has previously been used for, the method seems to be applicable for the purposes of the present study as well.

4.2 Steps and results of network analysis

The data of the nodes (factors) and edges (effects) that has to be imported into the Gephi software is presented as a matrix in Table 2. A non-zero number at the intersection of factors in the matrix shows that an effect from a preceding factor to the following factor exists. To study the connections in a qualitative manner, different weights in the effects are presented. The principle of weighting in this case is the following. First, the sum of the weights of all incoming connections to each factor is fixed to one (1). Secondly, when multiple incoming connections exist, they are weighted (based on the opinion of the present authors) on the basis of the order and magnitude of their significance for the target factor in question. In the case of the effect being presented by the equation in the literature, all the effective factors in question are weighted equally. In many cases, however, the weights can be presented only as estimations of the importance of the connection. The matrix shows the sum of the weights to incoming and outgoing connections regarding each factor.

To analyse the relationships between factors, first, the data presented in Table 2 were imported into the Gephi software. Then the software generated the relationship network presented in Figure 2. The principles for the generation of the network by Gephi are presented below.

In the network in Figure 2, the node and label sizes indicate the eigenvector centrality of each node. The eigenvector centrality is a measure of the importance of the node in the network on the basis of the node's connections (Bastian et al., 2009). The nodes in the network are scored relatively on the basis of the principle that connections to high-scoring nodes make a greater contribution to the score of the node in question than an equivalent connection to low-scoring nodes. This principle is presented in the paper by Bonacich (1972). The centrality scores generated on the basis of the principle are presented in Table 3.

The thickness of the line between the factors in Figure 2 indicates the strength of the connection (the size of the weight) in question. The thickness is equal to the sum of the weights of the effects in both directions. The colours in the network indicate the commonality of factors by means of grouping. These groups are found by optimising modularity locally in the connections network on the basis of the so-called Louvain Method (Blondel et al., 2008). The optimisation is performed in the following way. First, each node in the network is a community. Then, for each node the neighbouring nodes (those with which a node has a connection) are considered. Each neighbouring node is then placed into the community for which the gain in modularity is the maximum (the largest weight between the nodes). In the case of a tie, the method uses a tie-breaking rule. This process is repeated iteratively and sequentially for all the nodes until a maximum modularity is obtained.

As Figure 2 shows, five groups are generated, which are based on the Louvain Method presented above. These groups are visualised in the same colour, together with the factors within them. These factors have the strongest relationships together since a maximum modularity is attained. Table 3 presents the groups (numbered from 1 to 5) for each factor.

Figure 3 visualises the groups (the commonality of the factors) in the original process model.

Table 2 Matrix of weighted effects. A non-zero number at the intersection of factors shows that an effect exists. The sum of the weights of all incoming connections to each factor is fixed to one (1)

	Effect on		Sum of outgoing																	
	Available capacity	Demand	Total work content	Number of tasks	Number of workers	Job-related experience	Professional knowledge	Cooperation skills	Sense of responsibility	Self-confidence	Percentage of machine-paced work	Learning rate	Task variety	Task time	Task cooperation efficiency	Task-related skills	Job autonomy and responsibility	Self-efficacy	Deviation of task time from standard	Task completion time
Available capacity	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total work content	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Number of tasks	0	0	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Number of workers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Job-related experience	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0.2	0	0	0	0.05	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Professional knowledge	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cooperation skills	0	0	0	0	0	0	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sense of responsibility	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0.35	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Self-confidence	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of machine-paced work	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Learning rate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Task variety	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0	0
Task time	0	0	0.5	0	0	0	0	0	0	0.5	0	0	0	0	0.05	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Task cooperation efficiency	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.2	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Task-related skills	0	0	0	0	0	0	0	0	0	0.35	0.1	0	0	0	0	0.35	0.1	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.15	0
Job autonomy and responsibility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0.2	0	0	1	0	0	0	0.2	0	0	0.3	0	0
Self-efficacy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	1	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0
Deviation of task time from standard	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Task completion time	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 2 A relationship network of factors (see online version for colours)

The groups located in the process model in Figure 3 (as well as in the relationship network in Figure 2) are characterised as follows. The group #1 (yellow–green) covers the factors of *system base characteristics* together with *takt time*, which is also the best-scoring factor in this group (eigencentrality in Table 3). In the group #2 (green) together with several factors concerning *worker outcome* and *response*, the most of the factors concerning *worker base characteristics* and *task-related competence* are connected. The connections are relatively complex, which is also shown in Figure 2. This group covers the two highest-scoring factors. As shown, *job satisfaction* clearly outperforms the other factors in importance (eigencentrality), followed by *work motivation*. In the group #3 (purple) a relatively clear path in terms of sequential strength connections is shown (Figure 2). In this group *task characteristics* affect *learning and forgetting*, which contributes to *task-related skills* and to the *processing rate*. Then, the *processing rate* clearly affects *task completion time*. In the group #4 (red), *system performance* is at the centre. This is closely connected with a cause of system imbalance (*deviation of task time from standard*) and a flexible way to respond (*task cooperation*). In the group #5 (blue), the process target factors *production costs* and *tenure length* are connected to the factors concerning change in a workforce (e.g. *labour turnover* and *worker resignation or dismissal*). In addition, in this group, the worker's *job-related experience* and *tenure length* are connected to *professional knowledge*. *Cross-training or training* is the best-scoring factor in the group #5.

Table 3 Centrality scores and groups of factors

<i>Factor</i>	<i>Centrality score</i>	<i>Group No.</i>
Job satisfaction	1.000	2
Work motivation	0.788	2
Cross-training or training	0.740	5
Worker resignation or dismissal	0.634	5
Job autonomy and responsibility	0.560	2
Production costs	0.556	5
Self-efficacy	0.539	2
Job enrichment	0.500	2
Absenteeism	0.484	2
Processing rate	0.474	3
Learning and forgetting	0.446	3
Task-related skills	0.433	3
Takt time	0.422	1
Tenure length	0.421	5
Number of workers	0.383	1
Experience of success or failure	0.378	4
Amount of WIP	0.371	4
Cooperation skills	0.323	2
Labour turnover	0.315	5
Task cooperation	0.286	4
Deviation of task time from standard	0.274	4
Task cooperation efficiency	0.258	2
Idle time	0.255	4
Task variety	0.204	3
Throughput	0.181	4
Learning rate	0.175	3
Professional knowledge	0.163	5
Task completion time	0.154	3
Sense of responsibility	0.146	2
Number of tasks	0.143	1
Cycle time	0.126	4
Job-related experience	0.104	5
Self-confidence	0.091	2
Available capacity	0.073	1
Demand	0.073	1
Percentage of machine-paced work	0.032	3
Total work content	0.026	1

Figure 3 Groups located in the process model (see online version for colours)

5 Discussion

According to the results (Figures 2 and 3, and Table 3), the most important findings can be listed as follows:

- 1 the network analysis method used increases the understanding of the relationships between the factors by visualising the importance, connections and grouping of factors (Figure 2)
- 2 the centrality score of a factor (Table 3) as a measure of the importance of the factor on the basis of its connections shows the essentiality of each factor in the model presented in Figure 1
- 3 the grouping based on the maximum modularity of factors mostly separated operations- and human-related factors into their own communities, though exceptions were also found (Figure 3)
- 4 by weighting the effects between the factors, on one hand, clear sequential connections and, on the other hand, strong individual connections between the factors can be found (Figure 2).

The findings (2)–(4) listed above are discussed in more detail below.

Finding (2): *Job satisfaction* scored best, thus being the major link in the relationship network, followed by *work motivation* and *cross-training or training* and *worker resignation or dismissal* (Table 3). What is noteworthy is that all four of these factors are

located close to each other in the model (Figure 3), highlighting the relevance of *worker outcome*, as well as *system* and *worker response*, in this study.

Finding (3): Some degree of separation between the operations- and human-related factors in terms of grouping can be seen as a result of the nature of the connections. The mutual effects of human-related factors are inexact and complex, and their existence in the model is based on many previous separate studies as well as on the opinion of the present authors. These facts contribute to the large number of connections between certain factors in the present model (Figure 3). Operations-related factors, on the other hand, can be presented more often in the form of mathematical equations. This is the case, e.g., with *takt time* or *amount of WIP*. This again appears as factors that are strongly linked to each other (Figure 3). Some groups [groups #3 (purple) and #5 (blue) in Figure 3], however, represent operations- and human-related factors equally. In these groups the connections of both factor types to common and to separate factors in terms of performance and targets of the process can be identified. Also the connections between different types of factors can be further examined.

Finding (4): Clear sequential connections through the factors of *task characteristics*, *learning and forgetting*, *task-related skills* and *task performance* show the ways in which operations- and human-related factors are essentially linked together in the model (Figures 2 and 3). In general, these types of paths help to identify the factors that have an impact on the most important ones. Different loops between the factors can also be identified. Weighting based on the fixed sum of incoming connections also reveals where a single connection between two factors is especially strong in the model (Figure 2).

Although the results in terms of the relationship network increase the understanding of the nature and factors of human-assembly line combination, the investigation of such a complex socio-technical system as that presented in this study gives room for interpretation and criticism. This is due to the fact that factors can be selected in many ways and with many different definitions. The present study clearly focused on system-, individual worker- and task-related matters. Respectively, another study could focus on matters related to, e.g., ergonomics, incentives or teamwork. Moreover, the existence and weighting of a connection between the factors may divide opinion. Despite these facts, the investigation of the relationships between factors to the extent found in this study requires the information to be presented with a suitable level of accuracy and using an appropriate analytical method.

6 Conclusions and further research

This study made an analysis of operations- and human-related factors and their effects in the case of a manual mixed-model assembly line environment. The selection of factors for the analysis was based on the matters that are relevant in the environment in question. The information on the factors and their connections was primarily reviewed from the literature. The study handled factors in parallel and linearly in order to have a systematic and equal examination of both operations- and human-related factors. The mutual effects between the factors were weighted according to the importance of the effects. The factors and effects were imported into the Gephi software suite in order to analyse the importance, connections, and commonality of the factors by means of a relationship network. On the basis of the results, the following conclusions are drawn:

- the network analysis method that was used increases the understanding of the relationships between operations- and human-related factors by visualising the importance, connections and grouping of the factors;
- the importance of each factor in the system that was studied can easily be analysed on the basis of the connections between the factors, which helps to identify the essential factors in terms of assembly system performance;
- the grouping method reveals the possible commonality between the operations- and human-related factors and helps to identify their connections to common and to separate factors in terms of performance and targets of the process.

On the basis of the results, a network analysis method (Gephi) is applicable for analysing the relationships of factors in the complex system this paper studied. As a theoretical contribution, the factors and connections that were investigated separately in previous papers were investigated collectively in this paper. In addition, relevant intermediate factors were found. As a managerial contribution, the results of this study increase the understanding of the manual assembly line environment and further provide insights for decision making in daily management.

For further research, the factors presented here and the relationships that were identified can be utilised in a more thorough analysis of the present system. This thus also requires studies on factors and their effects to be reviewed more comprehensively. Additionally, the essential factors and relevant weights of the effects can be analysed in specific assembly systems. Some kind of sensitivity analysis of connections and weights is also recommendable. Finally, to get more accurate results from analyses, realistic parameter values have to be identified. This requires empirical studies to be carried out.

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Notes

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