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Richard Hedman & Peter Almström

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ARTICLE

A state of the art system for managing time data in manual assembly

Richard Hedman and Peter Almström*

Division of Supply and Operations Management, Department of Technology Management and Economics, Chalmers University of Technology, Gothenburg, Sweden

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Valid time data, a prerequisite for the efficient use of manufacturing resources, directly influence planning and control quality. However, access to time data that capture real shop-floor operations in general and manual operations in particular is often assumed by both academics and practitioners. This has led to a mismatch between reality and the data found in systems for production planning and control, causing operational inefficiencies and negatively affecting decision-making in manufacturing companies. This article addresses the importance of updated and valid time data in planning and controlling production and considers how they relate to manufacturing system performance and improvement. The focus is on how to determine, utilise, and sustain valid time data for manual assembly operations through integrating enterprise information systems. The article builds on a case study performed at a large manufacturing enterprise that operates a state of the art system for managing time data in manual assembly. Findings from the case study reveal how standalone system applications can be integrated with the organisational functions of an enterprise to achieve updated and valid operation times.

Keywords: time data management; production planning; production control; standardisation; work measurement

1. Introduction

Planning and control procedures have been identified as the two most important factors in improving manufacturing performance (Wacker and Sheu 2006). The fundamental difference between these factors is that production planning determines the planned values for variables in manufacturing, while manufacturing control determines the actual values (Lödding 2012). Both factors directly influence several competitive capabilities, such as resource use, delivery reliability, and cost (Vollmann et al. 2005; White 1996). Computers and digital information systems were introduced into production planning and control when IBM engineers developed the first material requirements planning system (MRP) in the 1960s (Hopp and Spearman 2008). This marked the initiation of a computer-integrated manufacturing paradigm from which numerous systems have evolved.

Today, concepts such as digital manufacturing (DM) incorporate the consistent use of digital tools and models in production planning and control, which are in turn integrated through continuous management of the planned and actual data values (Brettel et al. 2014; Zhang et al. 2014; Chryssolouris et al. 2009). In this context, the importance of data and information quality is well acknowledged (Dionne and Kempf 2011; Gustavsson and Wänström 2009; Pipino, Lee, and Wang 2002; Chae et al. 2014). In particular, valid data have proven to be critical to the successful implementation and operation of enterprise resource planning (ERP) systems (Umble, Haft, and Michael Umble 2003; Xu et al. 2002; Haug, Arlbjørn, and Pedersen 2009). Nevertheless, as stated by Saenz de Ugarte, Artiba, and Pellerin (2009), technology can ensure data availability but not data accuracy, and inaccurate data used as production planning and control input will lead to operational inefficiencies, for example, by causing extra work for production planners. Previous research has demonstrated that production planners tend to neglect actions proposed by system planners because they are unwilling to trust techniques they know are inadequate (Fransoo and Wiers 2008). Any detailed planning or optimisation also becomes unattainable if planning systems use inaccurate data (Ivert 2012).

This article addresses the acquisition and management of valid time data, a topic that, despite its importance in production planning and control, has been paid little attention in previous research. After an extensive survey of the relevant literature, Kuhlang et al. (2014) concluded that very few authors consider how time data are determined and that time data are often assumed to be already existent. Kuhlang et al. (2014) further argue that it is not uncommon for companies to refrain from implementing time-data-related functions in organisations as they are considered time- and cost-consuming. This is aligned with the findings of Almström and Winroth (2010), who identified a significant gap between the operation times specified in systems for material planning and control (MPC) and the operation times in reality. The study was part of the productivity potential assessment (PPA) studies

*Corresponding author. Email: peter.almstrom@chalmers.se

where the shop-floor efficiency in over 60 manufacturing companies was measured (Almström and Kinnander 2011). It was found that the planned times were initially determined incorrectly and that only about 25% of the companies ever updated their operation times once they had been inserted into MPC systems. The old operation times remained in the systems despite changes in working methods due, for example, to improvements, investments, and the introduction of new products. Allowances were added to compensate for disturbances and other unplanned losses. As the operation times were not updated, these allowances accumulated over time, increasing the gap even further.

Despite decades of automation initiatives, manual assembly is still one of the most cost-effective approaches in a context of high product variety (Hu et al. 2011). According to ElMaraghy and ElMaraghy (2016), assembly accounts for over 50% of total production time and 20% of total production cost. Nevertheless, determining and collecting time data for manual operations started to lose its significance in the early 1980s when both practitioners and researchers in the industrial engineering field started to distance themselves from the study and design of work (Bailey and Barley 2005; Kuhlang et al. 2014). The identified management unawareness of this problem suggests that companies risk overestimating their data quality and underestimating the impact of poor-quality data on their performance (Redman 1998; Almström and Winroth 2010). The purpose of the present article is to explore how valid time data can be ensured and sustained in the planning and control of manual assembly processes. This has been accomplished by evaluating a DM concept that constitutes a novel integration between enterprise information systems for resource planning, decision-support systems and operations technology that monitors and controls production processes. A case study was performed at a company that has implemented the DM concept in its department for final assembly of engines.

The article begins by reviewing the literature on the integration of enterprise information systems, including a morphology of time data management that defines the context in which the evaluated DM concept operates. This is followed by an industrial case study of a manufacturing enterprise that operates the system. The article concludes by summarising the findings of the case study and their contribution to improving the quality of time data in production planning and control.

2. Frame of reference

2.1. Integration of enterprise information systems

There are numerous enterprise information systems that acquire and use different types of manufacturing data in general and time data in particular. Much previous research on enterprise information systems has concentrated on single as well as integrated system solutions (Chryssolouris et al. 2009). For example, Dong, Xiao, and Zhang (2012) proposed a prototype architecture for assembly-oriented cyber–physical systems in an attempt to improve the real-time monitoring and control of assembly processes by integrating the physical assembly with the cyber process. Targeting global manufacturing companies and their final assembly plants, Lee, Leem, and Hwang (2011) presented a DM concept for integrating product data management (PDM) with ERP systems. This concept is intended to overcome the difficulty of constructing standard data relating to bills of materials and bills of processes in manufacturing because of the diverse manufacturing environments of each plant. Similar integration approaches are also found in engineering change management in which product lifecycle management (PLM) systems are integrated with ERP systems to manage the many changes resulting from shorter product life cycles and increasing product variety (Wu et al. 2014). Several integration initiatives related to computer-aided process planning (CAPP) systems have also been undertaken. As CAPP is a necessary step before writing assembly instructions, previous research has also attempted to extend assembly CAPP by incorporating assembly work instructions (Singer, Golan, and Cohen 2014). Integrating the functions of process planning and scheduling makes it possible to increase resource utilisation and reduce product delivery time through creating realistic and accurate production plans (Xu, Wang, and Newman 2010). However, in a state of the art literature review, Phanden, Jain, and Verma (2011) found that most research in this area has neglected industry-applicable systems, leading to a gap between the results of many research initiatives and corresponding real-life applications. Furthermore, Phanden, Jain, and Verma (2011) noted that many underlying models of process planning and scheduling integrations do not incorporate production disturbances, in fact resulting in infeasible production schedules. In addition, Schallow et al. (2012) stated that the use of DM concepts in planning processes lacks sufficient technological and methodological support, meaning that many data exchange operations must be realised manually.

Enterprise information systems depend on production data feedback from the real-world production environment. Shop-floor data are often managed using paper-based systems, which is both time-consuming and poses risks in terms of lost information (Saenz de Ugarte, Artiba, and Pellerin 2009). Liu et al. (2012) even claimed that on assembly lines with low-level automation, it is impossible to obtain real-time production data due to the absence of effective data acquisition systems. Nevertheless, recent decades have seen significant developments in automatic data acquisition systems. These primarily comprise manufacturing execution systems (MESs) that integrate

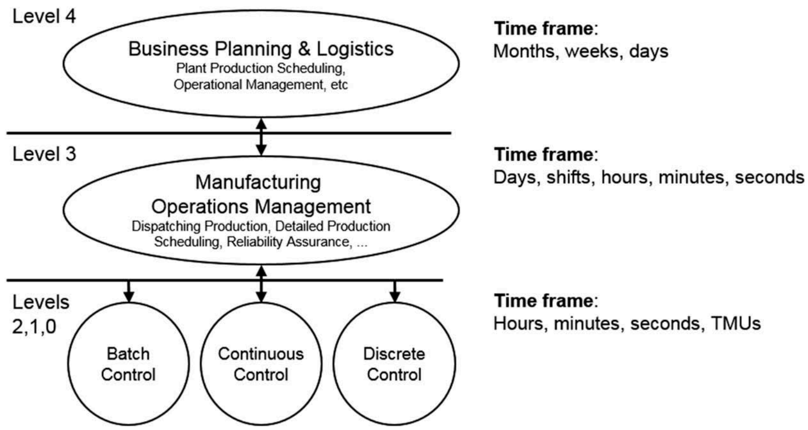

Figure 1. A functional hierarchy model of a manufacturing enterprise, adapted from ISA95 (2013).

sensors and programmable logic devices (PLCs) for monitoring and controlling actual production processes with the modelling of production, maintenance, quality, and inventory operations. This integration is also referred to as manufacturing operations management and corresponds to the third level in the functional hierarchy model of manufacturing organisations (Figure 1), defined in the international standard for enterprise control systems (ISA 95) (Scholten 2007).

The objective of MES is to optimise manufacturing processes and resources and to provide the higher-level systems, that is, ERP systems, with manufacturing data so they can manage enterprise operations such as business planning and logistics (Saenz de Ugarte, Artiba, and Pellerin 2009). An approach to developing a distributed MES that integrates ERP with operational-level systems has been proposed by Huang (2002). Despite industrial integration efforts, however, many companies and their ERP systems lack access to lower-level detailed and traceable production data, even though these data are directly related to key manufacturing cost drivers (Helo et al. 2014).

Information standards exist to provide best practices and improve the exchange and management of information between enterprise information systems (Chen and Vernadat 2004). The underlying architectures of enterprise information systems and the related standards incorporate information models of production systems and their resources (Steele, Son, and Wysk 2001; Nielsen 2003; Guerra-Zubiaga and Young 2008). Representations of manufacturing resources in such models generally include comprehensive definitions of activities performed by equipment resources; however, human resources and, consequently, manual activities are defined to a very limited extent and sometimes even neglected.

Consequently, the identified challenges that motivate this research concern integrated system solutions' applicability in industry, representations of manual operations, and focus on valid and updated operation times. The last is a large field in itself and is covered in the following section.

2.2. *Time data management*

This article uses time data management (TDM) as the umbrella term for the determination, application, and administration of time data in manual assembly. This view of TDM is based on the morphology of time data management defined by Kuhlang et al. (2014). It also constitutes the framework for describing the characteristics of the DM concept in the case study. In the morphology, general aspects of time data management are described using the attributes 'type of production', 'organisational assignment of TDM', and 'competence in TDM'. The organisational assignment of TDM, that is, whether and how companies operate TDM-related functions is, together with employee competence in TDM, especially important considering the causes of the identified gap between planned and actual operation times. General aspects of TDM also include how the actual time durations of operations capture the current work content and how this is reviewed. This is described by the attributes 'correctness of time data' and 'review of correctness of time data'.

Operation times are not static in manual assembly. Changes in product and process design affect the expected assembly work content and consequently the operation times used in process planning. As stated previously, integrating PLM and ERP systems is one way of managing such changes, while knowledge reuse is another. Mourtzis et al. (2014) presented a methodology in which similarities between past and new cases are measured to constitute the basis of a knowledge-based estimation of manufacturing lead time. The performance and actual duration of assembly operations are determined by the capabilities of individual operators and by production disturbances. Actual process times can be monitored to capture cumulative operator fatigue and calculate direct assembly costs to be used as input for dynamic job rotation scheduling, as proposed by Michalos et al. (2010). Kretschmer, Rulhoff, and Stjepandic (2013) applied data mining methods to existing planning data to conduct prospective evaluations of assembly work content and costs.

The TDM morphology of Kuhlang et al. (2014) includes four primary processes: time data determination, pre-processing, application, and administration. Each will be described in the following subsections.

2.2.1. *Time data determination*

The determination process is initially described by the attributes 'product emerge process (PEP) phase', 'controllability of manual work task', and 'extent of work content'. The PEP phase specifies whether time data are determined before or after the start of production. This, together with specifying the controllability of manual work tasks and the extent of work content, is used for choosing an appropriate time determination method.

For manual activities, the operation times used for the design, planning, and standardisation of processes should typically be determined through a method study (Zandin 2001). This is a systematic approach to finding the best method for performing an operation and includes the determination of a so-called standard time. Maynard's *Industrial Engineering Handbook* (2001) defines a standard time as 'the time required by an average skilled operator, working at a normal pace, to perform a specified task using a prescribed method, allowing time for personal needs, fatigue, and delay'.

Time standards can be established through estimates, historical records, and direct observation and measurement (Niebel and Freivalds 2003). The reproducibility and accuracy of time standards are significantly influenced by the time determination technique used (Kuhlang et al. 2014). As stated by Niebel and Freivalds (2003), time data determined from historical records will not indicate how long an operation should have taken but only how long it actually took. They further argue that no individual can establish consistent time standards based only on estimations. Consistent time standards for manual operations can therefore only be established by incorporating a predetermined time system (Zandin 2001). This is a motion-based technique for work measurement originating in the scientific management era when Frank Bunker Gilbreth was one of the first to assign standard times to basic elements of work. Today, there are over 50 predetermined time systems (Niebel and Freivalds 2003), some of the most commonly used are the family of Methods-Time Measurement (MTM) (Maynard, Stegemerten, and Schwab 1948) and the Maynard Operation Sequence Technique (MOST). Many Swedish companies use the MTM-based system, Sequence-based Activity and Method Analysis (SAM) (IMD 2004).

Applying predetermined time systems can be time-consuming. The attribute 'determination speed ratio' is defined by Kuhlang et al. (2014) as the ratio between work content and the effort to determine time data for the work content. This ratio is also linked to the selected time determination method. MTM-1 is an example of a very detailed time determination method that has a ratio of 1:200 (Niebel and Freivalds 2003). For the less detailed predetermined time system MTM-SAM, the ratio is 1:25–30 (IMD 2004). Consequently, there is a trade-off between the accuracy of the time determination method and the effort required.

2.2.2. *Pre-processing*

The TDM pre-processing step is intended to ensure that the determined times are application oriented. The morphology describes this using attributes that specify the type of time (i.e. actual time or target time) to be determined and the time-influencing factors that affect the work duration. The morphology also addresses how time data are presented and how the work is represented in process-building blocks. Kuhlang et al. (2014) incorporate in pre-processing the process-building-block category based on the hierarchical levels specified in MTM. As stated, the lowest levels of MTM consist of basic movements generally applicable to all manual activities. By definition, these movements become more specific when aggregated. Three process-building-block characteristics at different aggregate levels are defined by the product-neutral, product-related, and application-related attributes.

Furthermore, pre-processing also involves how time data are presented and their relationship with added value. In the lean production literature, manual activities are typically classified as value-added, supportive, or non-value-added activities (Liker 2005). Kuhlang et al. (2014) used the distinction between primary (i.e. value-added) and secondary (i.e. supportive and non-value-added) tasks.

2.2.3. *Application*

Time data can be applied in different ways in an organisation. In the application process, the first attribute, that is, 'level of time data application', describes whether the time data have strategic, tactical, or operational characteristics. This relates to the second attribute, that is, 'application purpose', which specifies the various internal and external applications of time data in a company. As stated by Kuhlang et al. (2014), time data can be applied internally for investment planning, workplace design, and order monitoring and externally as information related to supply chains and delivery planning.

2.2.4. Administration

The administration process is related to all three previously specified TDM processes. Three attributes are defined in the morphology that characterises the administration process: ‘data storage’, ‘administration system’, and ‘level of integration’. Time data can be stored in decentralised areas in the production lines or centralised on site or in the company. The data storage choice is related to the implemented time data administration system, in which Kuhlang et al. (2014) have categorised as specialised TDM IT systems, IT systems in production, or IT systems in planning. These systems also include spreadsheet solutions.

3. Research approach

This study examined how an organisation implements a DM concept that, on paper, has the technical ability to ensure that valid operation times are acquired and sustained. For this reason, the study had to be conducted using a research approach that emphasised both subjective and contextual interpretations of events. In information systems research, much effort has gone into laboratory experiments and field surveys emphasising the use of statistical analysis (Galliers 1990; Venkatesh, Brown, and Bala 2013). The main limitations of these approaches concern the difficulty of reproducing real-world environments (Benbasat and Zmud 1999). In comparison, the case study approach is typically used to generate empirical descriptions of particular instances of a phenomenon based on a variety of sources (Yin 2009; Eisenhardt and Graebner 2007). The case study is well established in information systems research as a means of studying the development and use of information systems in the field (Darke, Shanks, and Broadbent 1998). The method was therefore deemed suitable for studying the characteristics of the DM concept in an industrial context. According to Cavaye (1996), single-case studies can be applied in information systems research to enable deep exploration and to come as close to the research phenomenon as possible. Voss, Tsikriktsis, and Frohlich (2002) specified the possible disadvantages of the single-case study design as concerning limitations in the generalisability of conclusions and bias in terms of misjudging the representativeness of single events.

The DM concept evaluated in the present single-case study was developed by two external companies (X and Y) previously cooperating in a research project with academics from Chalmers University of Technology. The project addressed a holistic approach to the life cycle of operation times in production planning and control. Company X is a software company specialising in real-time production follow-up and disturbance handling. Company Y is a consultant agency focusing on product and manufacturing development; it also develops and markets software for process planning. The two companies developed and commercialised a prototype of the integrated system solution together with the engine manufacturer, independently of the researchers from Chalmers University of Technology.

3.1. Data collection

Multiple sources of evidence were used during the data collection. The researchers were initially trained in operating the process planning function of the DM concept. Site visits were made to the engine factory to interview production engineers and operators, and system developers from companies X and Y were also interviewed. In addition, the researchers were given access to a set of historical follow-up data from when the DM concept was first installed. Data for 10 weeks of normal production were extracted and used to analyse the time data and the disturbance handling function.

The factory where the case study was performed can be divided into different subsystems for engine machining, assembly, painting, and testing. At the time of the study, the DM concept was implemented only in the subsystem for the final assembly of one of the three engine types that the company produces; this therefore constitutes a natural system boundary for evaluation. The subsystem consists of two serial assembly lines with five workstations each. The engines pass through assembly line 1 before being painted in a robot cell and thereafter finished in assembly line 2. In total, 48 variants of the engine can be assembled in the subsystem. During the period covered in the acquired dataset, 14 variants were assembled, three of which constituted approximately 80% of the total quantity of 364 units.

4. System description

The DM concept integrates two established enterprise IT systems for process planning and for acquiring and managing shop-floor data; both these systems are operated as stand-alone applications by several companies. As their integration results in a system that manages the definition of planned values (e.g. time data determination, pre-processing, and application) as well as the acquisition of actual values (e.g. actual order execution times and disturbances), the integrated system is henceforth referred to as the TDM IT system. An overall functional description of the TDM IT system is presented in Figure 2. As seen, the TDM IT system is integrated with the company’s ERP

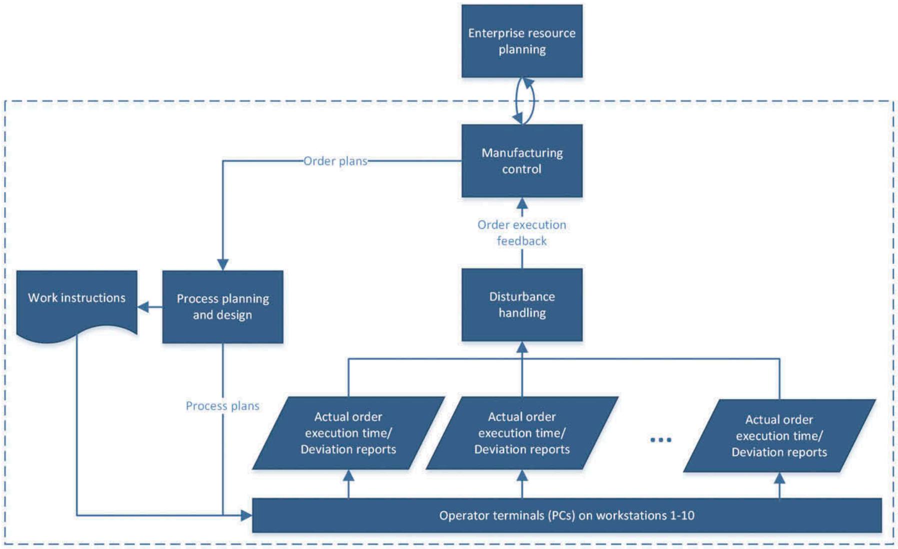

Figure 2. Functional description of the TDM IT system.

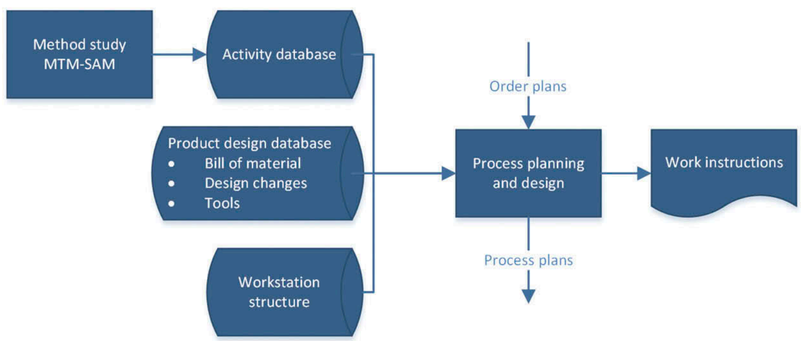

Figure 3. The elements of process planning and design.

system, but the evaluation of the DM concept is limited to levels 0–3 of the ISA 95 hierarchy (Figure 1).

The software for determining time data is incorporated into the process planning and design function. The software includes the administration of line balancing and assembly instructions as well as the management of process and design changes. For each product variant, the standard times for all on-going activities are defined using MTM-SAM. The process-building blocks of MTM-SAM are directly linked to the digital work instructions and, if applicable, to the required tools and to the components to be assembled (Figure 3). The order-specific assembly instructions are published on interactive touch screens positioned at each workstation. This means that instructions, tools, and components automatically follow their corresponding activities if they are moved between work stations during, for example, line balancing, which enables the actual material consumption to be traceable. Consequently, every time a production engineer changes an activity design or removes or adds components or tools, and the corresponding assembly instruction will be updated automatically.

Operators register on a workstation and can also choose the level of detail at which the assembly instructions are presented; for example, a novice might require detailed instructions, while a more experienced operator might prefer instructions at a more aggregated level. The TDM IT system keeps track of which version of the work instructions each individual has used. This means that if a design change has been made, resulting in updated work instructions, the assembler will automatically be notified when logging on to the workstation's terminal.

Changes in product design are managed through interoperability with the PDM system. The process planning function incorporates the same component identification tags as used in the PDM system. The product designers can thereby access the assembly instructions and evaluate how changes in product design affect both cycle time and work content at the work stations.

Table 1. Description of selected TDM attributes for determination and pre-processing.

	Attribute	The TDM IT system's characteristics
Determination *Specifies time values for defined work content*	Product emerge process phase	Time data are determined prior to start of production.
	Controllability of manual task	The assembly lines are manually driven, and operators have full controllability of all tasks
	Extent of work content	The duration of work is recorded in seconds, and the average cycle time for at each workstation is between 10 and 12 min.
	Type of time determined	Target times for planned activities.
	Methods to determine time	Predetermined motion time systems (MTM-SAM) and, standard data building blocks.
	Determination speed ratio	The speed ratio defined for MTM-SAM is nominally 25–30:1.
Pre-processing *Makes determined times application-oriented*	Type of time applied	Standard data which specifies target times for work elements, and describing the duration of work processes.
	Category of process building blocks	The work content can be depicted from the product-neutral level (basic operation) aggregated up to application related (e.g. calculation of product variants).
	Reference to added value	Includes reference to both primary (value added) and secondary (supportive and non-value added) tasks.

The central function of the TDM IT system is directly related to the general attributes 'correctness of time data' and 'review of correctness of time data'. Planned order time corresponds to the sum of the target cycle times of each work station that the engine passes. The production follow-up part of the TDM IT system operates similarly to level-three systems in the ISA 95 hierarchy. It automatically records data when an operator logs in at a workstation to initiate or continue with an order. The duration of each initiated order is measured in real time at each workstation. If the actual order execution time (AOET) at a workstation exceeds the target cycle time, the operator is required to file a deviation cause report. This is done by selecting one of the following seven predefined loss causes that will appear on the screen for assembly instructions:

- performance loss
- material shortage
- waiting
- start-up loss
- interruption
- equipment breakdown
- adjustment

When filing deviation cause reports, operators can choose to add comments to clarify the cause of the loss. In the manufacturing control function, it is possible to categorise and filter deviation reports, comments, and AOETs according to product variant, workstation, individual order, and individual operator. The purpose is to identify areas of improvement related to work content, product design, and need for training and supporting tools. The AOET of each order can be reported back to the ERP system to constitute the basis for price setting.

4.1. Specific TDM characteristics

The TDM morphology was developed to provide a holistic view of the TDM processes and to identify best practices in time data management (Kuhlang et al. 2014). This section accordingly describes the TDM IT system in relation to the defined processes and their corresponding attributes. With a determination speed ratio of 25–30:1, applying MTM-SAM is faster than using more detailed predetermined time systems, though it could still be considered time-consuming. To overcome this, the TDM IT system arranges the process-building blocks of MTM-SAM into variant reusable strings (Table 1). This means that all 48 product variants can be described using different combinations of 13 current variant strings. If any modifications (i.e. due to method improvements or product design changes) are made to an activity in the database, the related variant strings will also be updated automatically.

The TDM IT system is primarily applied at a tactical level for digital assembly instructions, line balancing, work system design, and order monitoring (Table 2). It is a cloud-based system, which makes it possible to retrieve assembly instructions, process planning data, and real-time production follow-up data from anywhere as long as there is an Internet connection and access to the servers.

5. System evaluation

The case company has a long tradition of applying predetermined time systems and its employees are competent in the time data determination processes. This means that the employees can apply time determination techniques autonomously and accurately (Kuhlang et al. 2014). This is important because, even though the engine

Table 2. Description of selected TDM attributes for application and administration.

	Attribute	The TDM IT system's characteristics
Application ***Provides time data for strategic and operative issues***	Level of time data application	Currently applied on a tactical level for work system design and order monitoring.
	Application purposes	Design-oriented (e.g. workplace design), order-oriented (e.g. order monitoring) and product-oriented (e.g. product design)
Administration	Data storage	Cloud based
	Administration system	Specific TDM IT system
	Level of integration	Fully integrated with interfaces between all TDM processes

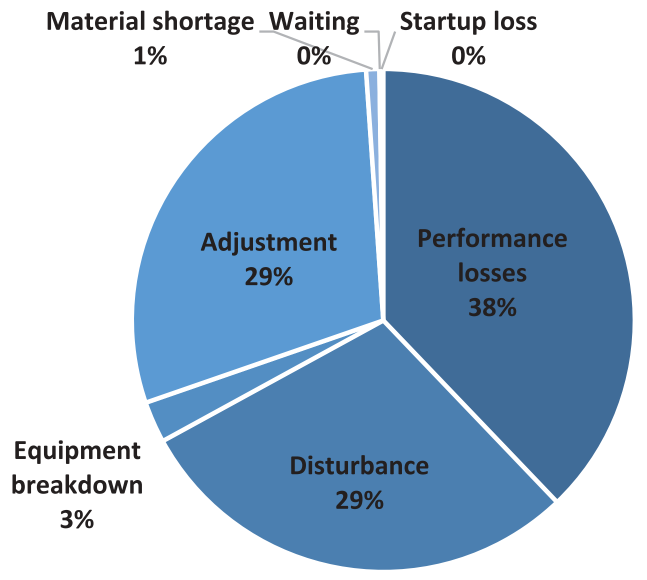

Figure 4. Distribution of recorded loss time.

manufacturer is part of a global group, the organisational assignment of the TDM function is local and there are large differences in how time data are managed between the companies in the group. One author of this article is a board member of the Nordic MTM association. Based on that author's experience from other companies, the engine manufacturer can be classified as following the current best practice in the Scandinavian countries. It can thereby be argued that operation times are being determined correctly.

Besides introducing new products, the case company implements approximately 200 design changes and 150–200 process changes per year in existing product variants. Design changes can range from replacing smaller components to larger product design modifications. Process changes encompass work method improvements as well as material supply improvements, line balancing improvements, the introduction of supporting tools, and the training and education of operators. The interoperability of the PDM system as well as the seamless integration between process-building blocks and assembly instructions in the process planning function ensure that planned operation times are kept updated for all product variants. The interview results indicated that the minimal manual administration required to manage changes and the high-precision traceability of material consumption were the main perceived benefits of the TDM IT system.

As stated, Liu et al. (2012) argued that it is impossible to acquire real-time information from manual assembly lines with low levels of automation, proposing a radio-frequency identification (RFID)-based solution. The TDM IT system does not incorporate the geographical tracking and tracing capabilities of an RFID solution. However, this study proves that a conventional MES solution can indeed be used to capture real-time data in manual assembly focusing on high-precision disturbance logging. Figure 4 shows the distribution of reported losses corresponding to 74.3 h of cumulative loss time out of 1050 h of production. Product variety, individual differences among operators, and a serial assembly line design are factors typically related to balancing losses (Fisher and Ittner 1999). In the TDM IT system, the balancing losses are supposed to be captured in the 'waiting time' loss category. However, as seen in Figure 4, this category is more or less non-existent. One explanation is the current low demand for the particular type of engines produced at this site. During the data collection period, only one out of five workstations per assembly line was staffed. This means that the operators follow the engines downstream from workstation to workstation, eliminating any potential balancing losses. With only one engine and operator per assembly line working independently, the production system also appears robust to disturbances. This is problematic from a TDM perspective, as the need for this type of detailed follow-up data will not be as obvious.

In addition, analysis of the historical follow-up data revealed that the meanings of the predefined loss categories were interpreted differently among the operators, naturally affecting the quality of the acquired data. When losses are reported according to predefined categories, it is vital that everyone in the organisation understand the meaning of each category in the same way. Thanks to the assemblers' comments when reporting stop causes, it was possible to determine whether a loss was reported inaccurately. For example, an interruption due to a breakdown, planned meeting, or a break was reported as a performance loss on several occasions. In general, two types of performance losses can be distinguished: skill-based performance losses determined by the individual's previous training and experience, which affect the ability to perform specific activities relative to the standard time (Almström 2013), and personal performance losses determined by the individual's physical ability and his or her motivation to perform activities relative to the standard time (Almström 2013). Therefore, knowledge of operators' personal and physical abilities in conjunction with valid target times is a prerequisite for managing performance variation among individuals (Niebel and Freivalds 2003). Such knowledge would also enable the use of existing system functionalities such as individual pace rate and dynamic balancing of the assembly line. Consequently, it is important to use the follow-up data to identify the causes of performance losses even when demand is low. The comments made it clear that when reporting performance losses, operators were inclined to explain the cause of the performance loss. The most frequent comments were either 'slow', which could be related to skill-based performance losses, or 'under training', which can definitely be related to skill-based performance losses.

In summary, the TDM IT system represents the successful integration of two established enterprise IT systems for process planning and production follow-up, operating in a real-life context. Standard times for each product variant and, consequently, planned operation times are determined accurately and kept updated through continuous evaluation against the AOET and through interoperability with the PDM system. The integration with the ERP system also ensures that price-setting decisions are based on actual performance outcomes on the assembly line. However, one identified limitation is that, even though the TDM IT system has been described in relation to the ISA 95 standard, the integrated system solution incorporates none of the existing information standards. It is a custom-built system for the case company, which limits the TDM IT system's capacity for upscaling and further integration with other applications.

6. A conceptual framework

Previous research has demonstrated that the quality of input data is central to planning and control (Chae et al. 2014; Gustavsson and Wänström 2009; Dionne and Kempf 2011), but that the determination of time data is often neglected by academics and practitioners (Kuhlang et al. 2014). In addition, the review of the literature on integration of enterprise information systems, presented in Section 2.1, found that several existing integrated solutions are limited in their industrial applicability and in their capability to represent manual operations. The described and evaluated TDM IT system has the technical capability to meet these challenges. However, as indicated by the case study findings, technology

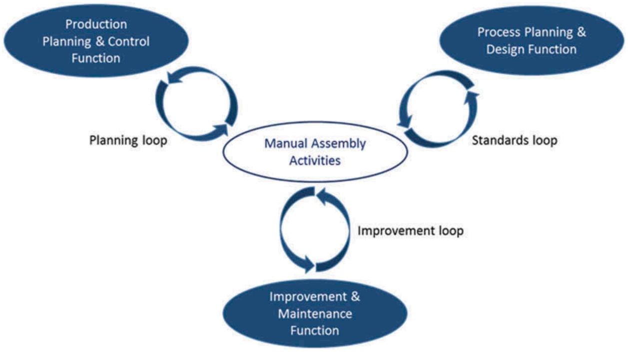

Figure 5. The lifecycle approach to operation times.

is in itself insufficient to ensure the quality of time data unless there also is a well-functioning TDM organisation. In the following section, a conceptual framework is therefore proposed together with a lifecycle approach to operation times. This illustrates how organisational efforts can be aligned, with the support of the TDM IT system, to ensure valid and updated operation times in manual assembly.

The lifecycle approach to operation times requires that production systems be viewed from a bottom–up perspective. Shop-floor activities are therefore central, and the procedures related to the lifecycle approach can be described in three loops, that is, standards, planning, and improvement (Figure 5). These loops are interdependent, meaning that the qualities of the functions 'production planning and control', 'improvement and maintenance', and 'process planning and design' depend on each other. This framework also represents the integration of all the actors who either affect or use the operation times, including everyone from product designers, production engineers, and production planners to operators. The three loops are described in more detail below.

Time data are determined based on the design of shop-floor activities, and they constitute the foundation for developing standards for process planning and design. These standards are, nevertheless, only of interest if they accurately represent the operations performed, referring both to the work content and its duration. Consequently, they need to be continuously evaluated in a 'standards loop' in which their validities are assessed in relation to the real-life operations they represent. In general, the application of time data determination techniques can be time-consuming and thereby be considered costly, especially if accurate time data for operations are non-existent to begin with. However, the planned versus actual time durations of shop-floor activities constitute the foundation on which many tactical and strategic decisions are made. Assumptions will always be made when shop-floor measures are aggregated higher up in organisations. Nevertheless, if the aggregated core data are based on estimates instead of facts, the outcome will be misleading.

At a higher level, the 'planning loop' relies on accurate data concerning manufacturing performance and the outcome of manufacturing processes. This loop is influenced by the capabilities of assigned resources and by the disturbances in the system. Production follow-up systems capture this, but the quality of production planning and the results of control policies can only be assessed in relation to valid standards, which in turn are derived through the standards loop.

The third and final loop of the lifecycle approach concerns improvements, and it bridges the 'planning and control' and 'process planning and design' functions. The continuous and systematic evaluation of planned versus actual values identifies improvement potentials, which need to be managed systematically as well. In the 'improvement loop', initiatives are prioritised and directed to improve either the standards, through method improvements or investments in new equipment, or the overall performance, in order to reach existing standards by reducing disturbances and improving the capabilities of resources.

7. Conclusions and further work

This article addresses a topic that is at the centre of the ongoing digitalisation of the manufacturing industry; how to acquire reliable input data, and based on a synthesis of the result can the following conclusions be drawn:

- It is possible to acquire reliable time data from manual assembly using the evaluated TDM IT system. This can be done cost effectively and with high quality of the resulting data, but the pre-condition is that there are clear definitions and standardised procedures for reporting stop causes and that the operators are trained in these procedures.
- The foundation for the TDM IT system is the use of a pre-determined time system, in this case MTM-SAM. Without this objectively correct input data, the system would only function as a way to measure the actual time.
- Several functions are integrated into the system, for example, dynamically generated digital instructions, quality assurance functions, and reporting of disturbance statistics. This integration is unique and state-of-the art for TDM IT, at least on the Scandinavian market.
- The proposed framework, clarifying the central functions of TDM and their relations, will further establish and advance TDM as a research field.

Reliable input data for manual activities open up a field of future research. Optimisation can become meaningful, and less manual work will be needed in the planning and control process. The TDM IT system is under further development, including a new architecture to be able to handle the large amount of data that future installations will require when more different sensor are connected to the system. Each component in each product will be traceable and associated with time of assembly, operator, different sensory data such as screw torque or temperature, and information about disturbances that occurred during the assembly. These data have the potential to lead to new kinds of analysis that in turn can lead to predictive and pro-active control of the production system. Disturbances and quality problems can be predicted and avoided, resulting in better delivery reliability, less quality issues, and lower costs.

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