Production Monitoring and Control with Intelligent Products

Gerben G. Meyer[*]

Department of Business & ICT, Faculty of Economics and Business, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands, +31 50 363 7194, Fax: +31 50 363 2275

g.g.meyer@rug.nl

J. C. ("Hans") Wortmann

Department of Business & ICT, Faculty of Economics and Business, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands, +31 50 363 6598, Fax: +31 50 363 2275

j.c.wortmann@rug.nl

Nick B. Szirbik

Department of Business & ICT, Faculty of Economics and Business, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands, +31 50 363 8125, Fax: +31 50 363 2275

n.b.szirbik@rug.nl

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[*] Corresponding author

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Abstract

Advances in production planning and control in recent decades have focused on increasing the sophistication of the planning function. For good reasons, these advances have led to the centralisation of the planning function in production. However, the sophistication of the planning function should be in balance with monitoring and control of the plan. Monitoring and control are by their nature decentralised, beginning on the shop floor, and, therefore, the desire for greater sophistication in monitoring and control leads to renewed interest in decentralised and localised approaches. This paper demonstrates the possibility of using intelligent products for decentralised monitoring and control. Intelligent products are aware of their local context and can negotiate with local manufacturing resources. As such, local solutions to problems can be proposed directly when problems occurs. With the advancement of the Internet of Things, such a scenario is likely to become feasible in the near future. The paper demonstrates the viability of such an approach through a simulation study, in which robustness is included as an additional measure of performance. The results of the simulations are encouraging.

Keywords: Intelligent Products, Production, Monitoring and Control, Disturbances

1. Introduction

This paper presents a new design approach for a monitoring and control system in the context of Production Planning and Control (PPC). PPC is concerned with reconciling the demand and the supply of products and materials in terms of volume, timing and quality. The activities required to achieve this are typically clustered into four broad functions: (1) *loading*, (2) *sequencing*, (3) *scheduling* and (4) *monitoring and control* (Slack et al., 2004). The first three collectively constitute the production planning function; the fourth the production control function. Advances in PPC over recent decades have mainly focused on increasing the sophistication of the production planning function. This has steadily resulted in centralised PPC activities.

There are good reasons for centralising the loading, sequencing and scheduling activities. From a materials perspective, centralised coordination of the supply chain reduces the bullwhip effect (Jordan et al., 2007; McCullen and Towill, 2002), by using appropriate rules for safety stocks and lot sizes. In addition, centralised coordination can solve the problems of matching sets of parts and balancing the supply streams of all components in an assembly's bill-of-material (Orlicky, 1975). From a capacity perspective, optimising one resource will usually have an impact on other resources. Given this situation, some form of coordination is not only useful but virtually unavoidable.

Monitoring and control cover the activities performed in order to react to disturbances. These activities may lead to deviations from the original plan (Slack et al., 2004). The vast majority of academic effort into PPC has been spent on the more sophisticated planning concepts, while monitoring and control has received much less attention (Vieira et al., 2003). However, planners in real life devote most of their efforts to monitoring and controlling, rather than carrying out planning activities (Herrmann, 2006; McKay and Wiers, 2006; Pinedo, 2008). This justifies a renewed interest in monitoring and control.

Centralised planning and control can have drawbacks concerning monitoring and control (e.g. De Snoo et al., 2007). Drawbacks appear due to the many small disturbances that occur. A well-known example is when a component is damaged just before it is needed in manufacturing. This is especially problematic in case of production of highly customized products, where buffer stocks are typically small or even non-existent, due to expensive components or order-dependent customization. Often, these minor disturbances are not even made known to the central planners, and simply solved at a more local level by the shop floor supervisor. Other examples of disturbances are production errors, machine failures, quality problems and shipment errors. As will be discussed in detail in Section 3, centralised planning and control systems typically have problems in handling with such disturbances, due to the applied aggregation and the hierarchical nature of these systems. The advancement of the Internet of Things however enables new system designs which might address these problems.

Based on these arguments, a new design approach for a monitoring and control system is presented in this paper. The main goal of this approach is to enable new ways in which disturbances can be dealt with, in order to increase the robustness of the overall plan execution. To investigate the potential of the proposed system design, computer simulations have been performed. The usual measures of performance in PPC studies are based on financial results (e.g. Collins et al., 2006). This paper however argues that profit as a measure of performance does not give sufficient weight to the impact of disturbances. Our fundamental observation is that studies focussing on production planning performance tend to ignore small disturbances, although these, in reality, dominate the planner's activities in practice. This paper aims to contribute by proposing the *robustness* of a monitoring and control system as an important additional measure of performance.

This paper is structured as follows. Section 2 will elaborate on the background and related work. Next, Section 3 will define the problem statement of this paper, based on an analysis of the problem area. The new design approach for a monitoring and control system will be presented in Section 4, and then evaluated in Section 5. The paper ends with a discussion and conclusions.

2. Background and related work

Monitoring and control of manufacturing equipment and automated control of manufacturing steps have made great progress in recent decades. In general, the term *intelligent resources* (Shen et al., 2006) is used to indicate manufacturing resources in modern factories that are being able to execute and control manufacturing activities, as well as being capable of monitoring and controlling their own status. Process quality parameters are monitored, such as tolerances in mechanical machinery, or pressures and temperatures in chemical equipment.

Many authors consider agent encapsulation as the most natural way to make resources intelligent (e.g. Saad et al., 1995; Bussman and Schild, 2000; Venkateswaran et al., 2003). In this context, an agent is defined as a software system that communicates and cooperates with other software systems to solve a complex problem that is beyond the capability of the individual software systems. Intelligent resources can react to manufacturing problems and investigate alternative machines and routes for products on the shop floor in the event of disturbances. Another approach is holonic manufacturing, in which a holon is defined as an autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects (Van Leeuwen and Norrie, 1997; Hribernik et al., 2006).

Although individual resources are becoming more intelligent and autonomous, integrating various intelligent resources has remained cumbersome due to their dedicated and propriety nature. In order to achieve interoperability among the various autonomous intelligent resources, an open, flexible and agile environment with "plug-and-play" connectivity is seen as essential (Jammes and Smit, 2005). As such, there is an increased interest in developing architectures that enable a more generic integration between intelligent resources. An example is the SOCRADES project, in which a device-level Service-Oriented Architecture for factory automation is being developed (Taisch et al., 2006). Furthermore, there is increasing interest nowadays in applying intelligent products and the Internet of Things (IOT) in manufacturing and supply chain management (Meyer et al., 2009). McFarlane et al. (2003) define an intelligent product as a physical and information-based representation of a product. This is the basic principle behind the IOT: all everyday devices will be enabled to connect to a data network (Gershenfeld et al., 2004). Figure 1 provides an example of a hard disk drive as an everyday device connected to a data network. A decision making agent is attached to provide the intelligence.

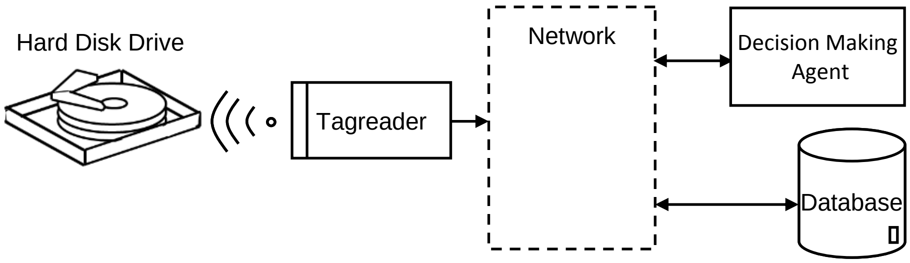

Figure 1: An intelligent product (Wong et al., 2002)

It is likely that in the future not only resources but all items and devices on the shop floor will become intelligent due to advancements in intelligent products and the Internet of Things (IOT). The interoperability between all these connected devices will be provided using the same data protocols that are currently used for the Internet (Gershenfeld, 2000; Fleisch, 2010). Therefore, the challenge is to determine how one can create manufacturing systems involving many intelligent items and resources that can work together and adapt to changes both on the shop floor level as well as on a factory-wide basis. This paper anticipates on these future developments.

3. Problem analysis

3.1 Analysis

The terms *monitoring* and *control* need elaboration in the context of a discussion about aggregation. Aggregation is widespread in PPC (e.g. Axsäter and Jönsson, 1984; Schneeweiss, 2004). The first observation is that most centralised systems aggregate over time. These systems perform loading, sequencing and scheduling tasks in aggregated time periods of months, weeks, days or even shifts. Secondly, centralised planning systems aggregate by location. Materials issued to the shop floor are booked as work-in-progress, but no information is available on *where* on the shop floor these materials are to be found. Thirdly, centralised PPC systems aggregate similar resources. Most factories have a number of machines which are similar but not exactly the same. Finally, centralised PPC systems aggregate over materials, because small differences are unmanageable in central planning systems. Nevertheless, these examples of aggregation are best practices in planning, and there is no obvious reason to change them.

Conversely, monitoring and control problems seldom present themselves in aggregated terms. Manufacturing and distribution problems usually occur in real time, not far away in a future period. Materials mislaid in a warehouse or on the shop floor are missing *now*. Quality problems leading to the production of scrap are always related to a specific machine, tool or operator. Resource problems relate to specific equipment that is no longer available and maybe in need of maintenance. Material problems are related to a specific piece, pallet, batch or other unit of processing. These are specific problems that occur in detailed, disaggregated form. Therefore, it takes humans to estimate their impact on the aggregated plans.

Another issue stems from the fact that planners using a centralised PPC system typically adopt a hierarchical approach. This has the advantage that the complexity on the various organisational levels is reduced, with each level able to function partially independent. However, performance feedback is important in hierarchical systems for proper functioning (Mesarovic et al., 1970). Therefore, appropriate and timely feedback has to be provided by the lower levels to the higher levels. Furthermore, the higher levels need to be able to respond adequately and in time to this feedback. If any of these requirements are not met, it becomes impossible for planners to effectively monitor the plan's execution. This problem has been referred to as the vertical communication bottleneck in organisations (Galbraith, 1973). Therefore, due to these issues, monitoring and control in the PPC context still largely relies on manual steps.

3.2 Problem statement

The fact that humans are needed to interpret problems in materials or equipment that have factory-wide consequences hampers further progress with PPC. Human expertise is generally not available around the clock, and humans have limited information processing capabilities. People cannot always know the exact manufacturing conditions and constraints in remote manufacturing facilities. When manufacturing problems are detected, they first have to be communicated and interpreted, then the PPC systems are notified and, finally, planners will react. Consequently, reaction to manufacturing problems by PPC systems and central planners is usually slow (Van Wezel et al., 2006). This analysis brings us to our initial problem statement:

> *Is it possible to design an automated monitoring and control system which works at the level of detail where problems typically occur and which can interpret these problems directly, then inform and propose solutions to the appropriate person (typically the shop floor supervisor) and, if necessary, provide feedback to PPC systems?*

3.3 Performance measures

The performance of PPC systems is generally studied in logistic and economic terms. Logistic performance measures include service levels of stock points, average lead times and due-date reliability. Economic aspects cover inventory levels, resource utilisation, overtime costs, profit margins etc. It is not easy to relate the performance of monitoring and control activities to such indicators. Therefore, the designed artefact described in this paper will also be evaluated in terms of its impact on the *robustness* of the larger PPC system. The argument is that the more problems that can be handled locally without even being observed in the wider PPC context, the better the system performs. To achieve this, a monitoring and control system should prevent small disturbances having large consequences.

4. Monitoring and control system design

This section describes the proposed design of a production monitoring and control system. First, the requirements are presented. Next, the main design properties of the proposed monitoring and control system will be described in greater detail.

4.1 Requirements for monitoring and control systems

As discussed earlier, centralised planning and control systems have problems in dealing with disturbances because they work with aggregated data. However, as disturbances seldom present themselves in aggregated terms, an effective monitoring and control system needs to work with data on the same level of detail as where the disturbances normally occur. This leads to the formulation of the first requirement:

R1: The system should work with data on the same level of detail as where disturbances occur.

Furthermore, it was stated that feedback from the machine level to factory-level PPC systems has remained problematic. Therefore, a monitoring and control system should be able to provide useful feedback about disturbances to the appropriate person in order to enable efficient handling of the disturbances and, when required, communicate this feedback to the factory-level PPC systems. This leads to the formulation of the second requirement:

> *R2: The system should be able to provide feedback about disturbances to the appropriate person directly when they occur and, if needed, communicate this feedback to the factory-level PPC systems.*

By using detailed, real-time disaggregated data, the search space available for a suitable solution to a disturbance increases significantly compared to the current situation. However, the large amount of information in this space can make it difficult to manually find a suitable solution. Therefore, if a person is to adequately respond to the provided feedback in a timely fashion, the support of a system which can search this space effectively is required. This leads to the final requirement:

> *R3: The system should be able to propose solutions to the appropriate person immediately when a disturbance occurs.*

Below, we explain how these requirements are incorporated in the system design, by applying the concept of intelligent products.

4.2 Structural design

Centralised PPC systems are generally inventory-based systems, built around material accounts and transactions between such accounts. Each account represents the quantity of a particular material in a specific location (Rönkkö et al., 2007). Such a location can belong to any warehouse or shop floor facility, or it can be a packing unit (e.g. a container or pallet) which can store material. A simplified UML class diagram of an inventory-based system is shown in Figure 2. As shown in the figure, an inventory-based system keeps track of the number of units of each product type stored in every location by means of a material account. Further, through transactions, the number of products of a certain type at a specific location can change. The inventory-based system design shows that no information is stored about individual products (Wortmann et al., 1996). This functionality of linking data to individual physical products is referred to as tracing, defined as the ability to preserve the identity of a particular physical product, as well as its complete history (Töyrylä, 1999).

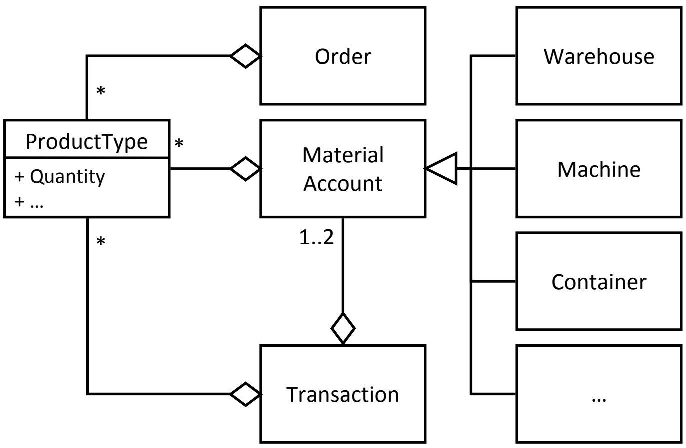

Figure 2: Inventory-based system

However, in order to meet this first requirement of identity preservation, the monitoring and control system has to be able to store detailed information on the level at which disturbances occur. Therefore, tracing functionality has to be incorporated in the system design. Accordingly, a product-centric (rather than an inventory-based) system design is adopted. A typical UML class diagram of a product-centric system is shown in Figure 3. As shown in the figure, the physical product item becomes a new entity in the system, replacing the product *type* entity which was associated with locations and transactions. In this new design, attributes such as location, type, quality and version can be stored for every individual physical product. Further, for each product, the physical operations through which it has been transformed into its current state can be stored. The location of each item can be more specific since there is no longer a need to aggregate over fixed locations. This approach enables monitoring and control on the level of individual products at which disturbances typically happen.

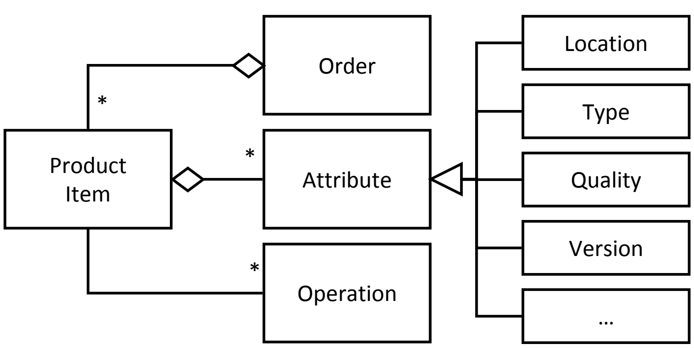

Figure 3: Product-centric system

4.3 Product agent behaviour

In order to collect up-to-date information on all products, to be able to detect problems and provide feedback to the supervisor, and to be able to propose solutions to these problems, some form of intelligence is needed. As discussed in Section 2, agents are considered the natural response to the need to implement the intelligence part of intelligent resources. Similarly, agents also seem best suited to implementing the intelligence part of intelligent products due to their knowledge and reasoning capabilities which can enable them to carry out most repetitive tasks. Therefore, in the system design proposed here, every product will have its own agent for performing these tasks. The behaviour of these product agents will be introduced below, according to the three levels of intelligence as distinguished by Meyer et al. (2009).

Level 1: Information handling

Firstly, product agents need up-to-date information. The most important information required by an agent if it is to execute its tasks properly consists of two parts: the current status of the product, and the planned or desired status of the product. Determining the desired status of the product is relatively easy, the agent can analyse information in currently applied PPC systems, such as order due dates and planned transactions and operations which will affect the product. However, determining the current status of the product can be more problematic. One approach is to re-examine the information already present in the current systems: this will reveal which transactions and operations have already been performed, and which still need to be performed. However, it is unlikely that this information will be sufficient since there may be delays between when a transaction is performed and when this is recorded in the system and, more importantly, the information will most probably be on a higher aggregation level. Therefore, in order to obtain up-to-date status information on individual products, auto-ID technologies, such as barcodes and RFID, will have to be introduced to uniquely identify individual products. Further, the location of a product has to be approximated using localisation techniques, as described by Strassner and Schoch (2002). Another method is to update the location status of a product each time its barcode or RFID tag is scanned and the physical location of the scanner is known (Huvio et al., 2002). These identification and localisation techniques can be combined with sensor technologies, such as those based on thermal, acoustic, visual, infrared, magnetic seismic or radar systems (Strassner and Schoch, 2002). All these techniques bring the “Internet of Things” to the shop floor.

Level 2: Problem notification

Provided the product agent has knowledge of the plan as well as the current status in terms of plan execution, it is enabled to detect disturbances. To achieve this, the agent employs a mechanism, such as a utility function, to determine whether progress matches the schedule and whether other status properties are still within an acceptable range. Such utility functions can be based on factors such as the amount of time remaining to the order due date, whether there is a proper plan to finish the product on time, whether the plan execution is on schedule, plus factors such as whether the product is within the desired temperature range. If an agent’s utility score drops below a certain threshold, the agent will enter a problem state, and can immediately provide feedback about the problem to the supervisor who then knows which precise product(s) on the shop floor are currently having problems.

Level 3: Decision making

Besides providing feedback on problems, it is beneficial if the agents propose solutions or suggest how to reduce the severity of the problem. As a result of the continuous information gathering, all agents are aware of the current situation. This enables the agents to negotiate in real-time about alternative plans to overcome the disturbance. However, it will not be feasible to let each product agent negotiate with all other product agents, especially when the number of products is high. Therefore, an auctioning approach based on the Contract Net Protocol (Smith, 1980) is proposed, one in which factory resources, such as machines, can offer their capacity, and product agents can bid for this capacity. The overall result of the negotiations between resources and product agents will be presented to the supervisor who can then decide whether or not to schedule the tentative actions. If the supervisor does not agree with parts of the schedule, changes can be proposed in such a way that the agents can learn new preferences from them. This approach is similar to the Escape and Intervention monitoring and control mechanism proposed by Roest and Szirbik (2009).

5. Evaluation

This section briefly describes how the proposed system design was evaluated through simulation experiments. A more thorough elaboration on these experiments and the results can be found in (Meyer and Wortmann, 2010).

5.1 TAC SCM

To compare the performance of the proposed system design, as described above, with existing designs, the TAC SCM simulated supply chain is used (Collins et al., 2006), due to several reasons. Firstly, it was designed to capture many of the challenges involved in supporting dynamic supply chain practices. Further, it is a well-founded framework, and widely reported in the literature (e.g. Gerding, 2009; Collins and Sadeh, 2009). Finally, the framework can be easily extended and modified for specific needs.

In a TAC SCM simulation, up to six competitors have to develop a PPC system for a otherwise identical computer manufacturer, which are competing with one another for customer orders and supplier components. The TAC SCM scenario from the perspective of a single manufacturer can be seen in Figure 4. As shown in the figure, a manufacturer has four major tasks to perform, namely negotiate with suppliers for components, bid for customer orders, manage the production schedule and manage the shipping schedule. Further, each manufacturer has an identical assembly cell capable of assembling any type of computer, and a warehouse that stores both components and assembled computers.

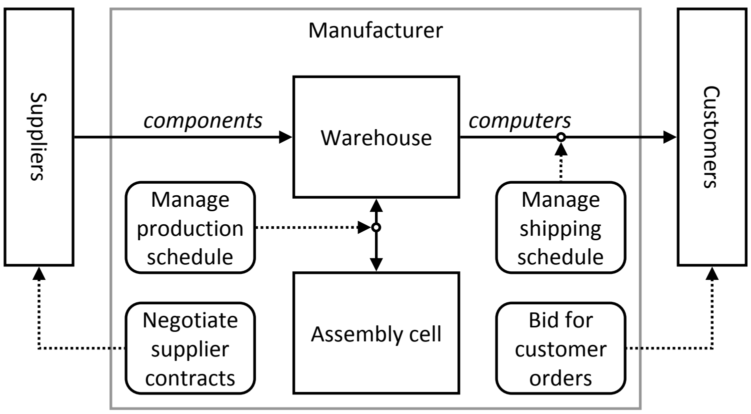

Figure 4: The TAC SCM scenario

Although there are some variations among the scenarios that manufacturers have to deal with, the standard TAC SCM 'game' purposefully excludes disturbances. For our purposes, to test the performance of a manufacturer in terms of monitoring and control aspects, a disturbance has been added to the game. In the slightly modified version of the game, every component which is delivered by a supplier to a manufacturer has an *n* percent probability of being rejected. When this occurs, the component will not be added to the manufacturer's inventory. This amounts to a material shortage disturbance, the most common disturbance in practice (Lindau and Lumsden, 1995). In reality, such disturbances can have a variety of reasons, such as components being damaged, broken, delayed or wrongly shipped.

Having added this disturbance to the game, experiments have been conducted with three arbitrary values for *n*, namely 0, 5, and 10. For each value of *n*, 26 simulations were conducted in order to achieve reasonable confidence in the results. In each simulation, the same four ‘competitors’ were used, namely: TacTex-07 (Pardoe and Stone, 2004; Pardoe et al., 2007), PhantAgent-07 (Stan et al., 2006), DeepMaize-07 (Kiekintveld et al., 2006) and Mertacor-08 (Chatzidimitriou et al., 2008; Toulis et al., 2006). These ‘opponents’ were chosen for their high rankings in recent TAC SCM competitions, as well as their availability on the Agent Repository of the TAC website (www.sics.se/tac). The next section of this paper describes the design of our proposed planning and control system which we implemented as a TAC SCM manufacturer. Following this, the results are presented.

5.2 TAC SCM manufacturer

The detailed description of the structure of the implemented manufacturer system for TAC SCM simulations (named GRUNN in the simulation experiments) can be found in Meyer and Wortmann (2010). The basic idea is illustrated in Figure 5, which shows a UML class diagram, in which the various internal agents of the manufacturing agent plus the warehouse and the assembly cell are depicted. As shown in the figure, there are four different planner agents in the system, each to perform one of the four basic tasks described earlier. In addition, the product agent has to perform the tasks described in Section 4.3, and is responsible for the complete processing of a single final product.

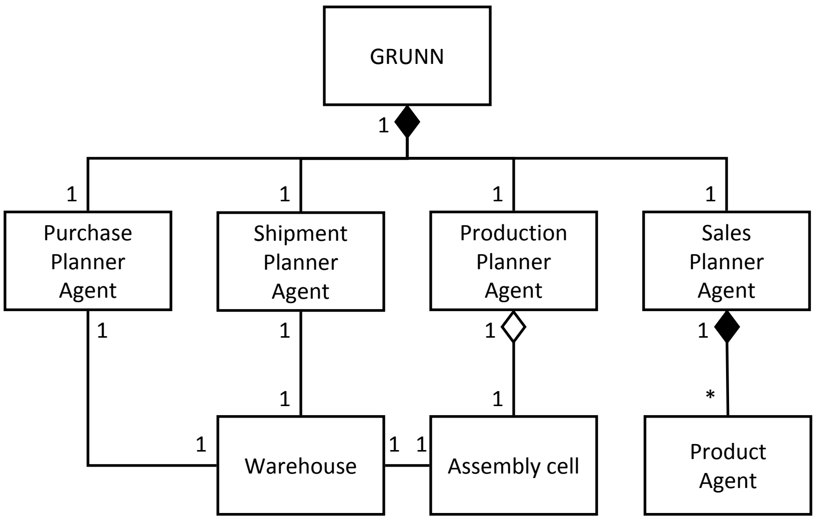

Figure 5: Class diagram of the manufacturer agent

In the TAC SCM simulation, one order is considered as one product in the system design presented above. This however does not have any consequences in implementing the structural design presented in Section 4.2. Further, as the TAC SCM simulation does not allow for negotiation with human planners, the product agents will not use the decision-making mechanism described in Section 4.3 in order to propose solutions, rather this mechanism will be used to create the overall production plan. As such, the responsibility of a product agent for completing an order covers the procurement of the components required for the assembly from the warehouse, the allocation of the required production capacity and arranging the shipment of the finished products to the customer. To achieve this, the product agents apply the behaviour as shown in Figure 6. The figure shows a UML communication diagram in which the communication pattern of a product agent with planner agents is illustrated. For each procurement task, an auction-based mechanism is used that results in a distribution of capacity among products based on priority.

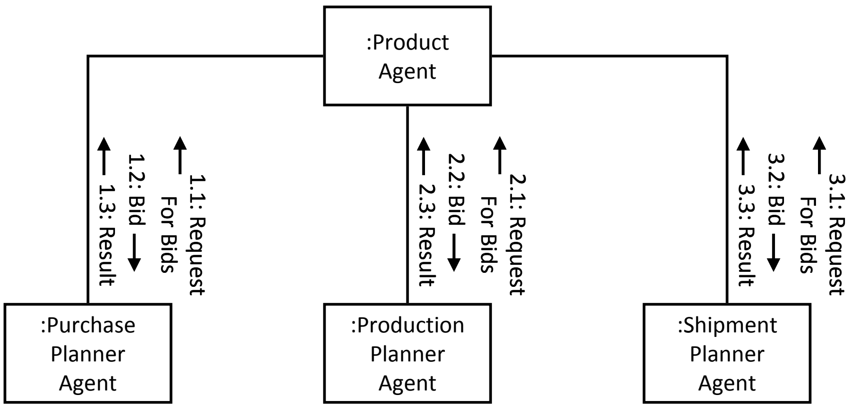

Figure 6: Behaviour of a product agent

The developed system will not result in the best possible plan because a centralised system is always able to find a more-optimal solution within a mathematical domain. Distributed systems are typically greedy and therefore suboptimal. However, as will be illustrated by the results in the next section, the system presented here can result in a very robust manufacturer.

5.3 Results

This section presents the results from the simulation experiments, as described above. Although the newly developed manufacturer system did not perform well in terms of profit (all the established competitors had a higher average profit), the new system did perform well when considering the robustness performance measure. This robustness measure is defined as the percentage of orders that are delivered to the final customer on time, i.e. the delivery of a specific order is on or before the due date. Figure 7 shows the results from the conducted simulations in terms of orders finished on time. The graph shows that the percentage of orders completed on time decreases for all established agents as the percentage of unusable components increases. Our modified system, GRUNN, performs much better in terms of this criterion: even when ten percent of all components are unusable, nearly all orders are finished on time. This observation confirms that an approach based on intelligent products is very effective in handling disturbances in the simulated scenario.

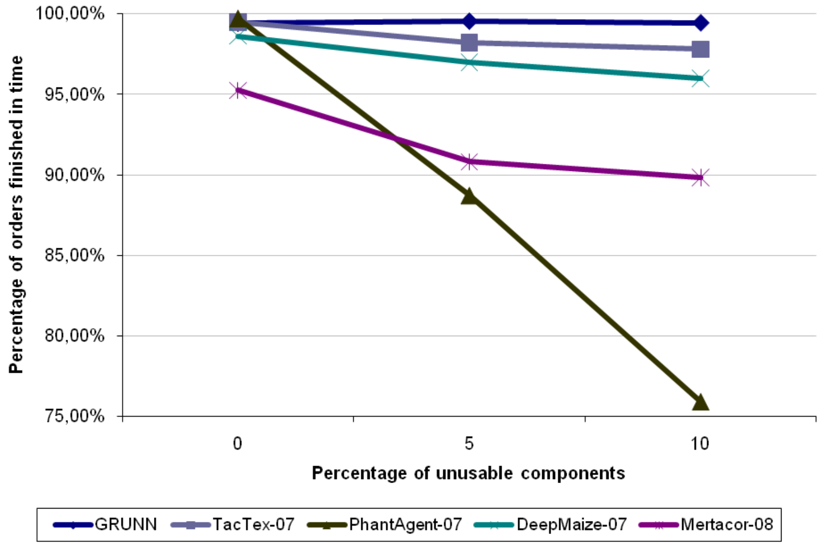

Figure 7: Performance of manufacturer systems in terms of orders finished on time

One obvious approach to overcoming the problem of unusable components is to increase the component inventory "safety stock" margin. Figure 8 shows the average storage costs per accepted order for each applied manufacturer system, and this gives a good indication of the inventory levels of each manufacturer. The figure clearly shows that using the GRUNN approach does not lead to a significantly larger inventory, and therefore that it is not dealing with the problem of unusable components by increasing safety stock levels.

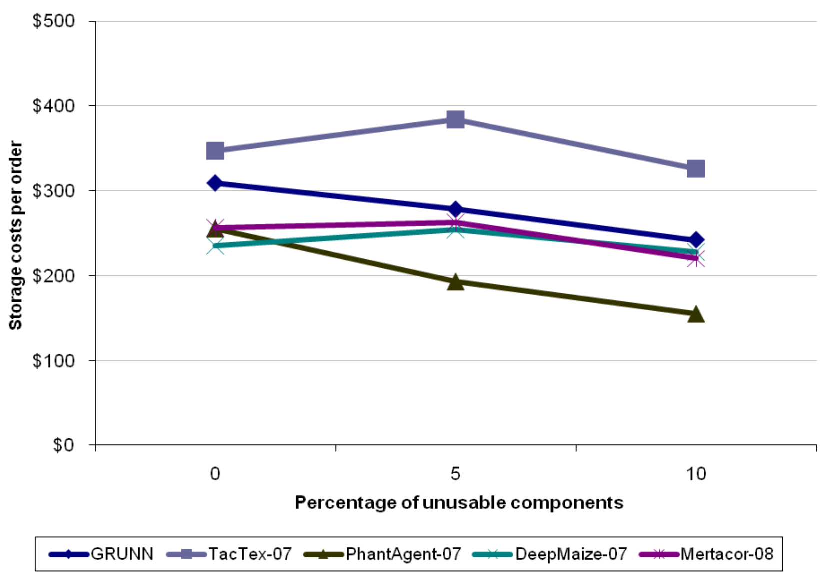

Figure 8: Manufacturer's storage costs per accepted order

6. Discussion and conclusions

Centralised planning systems in PPC is justifiable, especially when the focus is on classical performance indicators such as overall profit, utilisation of resources or integral service levels. The simulation results here also justify centralised planning as all the manufacturers using conventional approaches saw higher average profits than the proposed intelligent-product-based approach. This is not surprising: a central algorithm can always calculate the optimal solution in a closed and modelled world. In contrast, decentralised planning systems are normally not only myopic but also greedy, and therefore suboptimal, which leads to a lower performance in terms of profit.

However, during the execution of a manufacturing plan, disturbances can occur which can be solved in either a centralised or a distributed way. The simulation results presented in this paper show that the intelligent products approach is very robust in terms of handling such disturbances. As such, this approach seems to be promising as a monitoring and controlling system if robustness in performance is seen as an important factor.

In general, even if a simulated environment reflects disturbances in a realistic way, the simulation still only contains modelled versions of these disturbances. Once a model environment is fully specified, a centralised approach to optimisation will always outperform a distributed approach since it is always possible to calculate an optimal solution within a specific model. As such, we would argue that the claimed advantages of resolving disturbances locally, rather than centrally, needs to be validated beyond a simulated environment, in a real life setting, to discover the true potential of this localised approach. Although simulation is very valid in investigating the feasibility of PPC design ideas, real life experiments may demonstrate that an intelligent products approach will have larger benefits in practice where situations can always occur which are beyond the scope of the specified model.

Nevertheless, we accept that a central system is better in terms of creating an optimal plan, whereas an intelligent products approach for monitoring and controlling seems to be more promising in terms of robustness during plan execution. As such, we would argue that the "ideal" planning and control system would combine the best of both worlds. On this basis, future work should focus on investigating how a production planning and control system for a manufacturer can be improved by combining a centralised planning approach with a localised monitoring and control approach through the use of intelligent products.

References

Axsäter, S., and Jönsson, H., 1984. Aggregation and Disaggregation in Hierarchical Production Planning. *European journal of Operations Research*, 17, 338-350.

Bussmann, S., and Schild, K., 2000. Self-organizing manufacturing control: an industrial application of agent technology. *In Proc. of MAS'00*, 87-94.

Chatzidimitriou, K.C., Symeonidisa, A.L., Kontogounis, I., and Mitkas, P.A.,2008. Agent mertacor: A robust design for dealing with uncertainty and variation in scm environments. *Expert Systems with Applications*, 35 (3), 591-603.

Collins, J., Arunachalam, R., Sadeh, N., Eriksson, J., Finne, N., and Janson, S., 2006. *The supply chain management game for the 2007 trading agent competition*. Technical report, School of Computer Science, Carnegie Mellon University, Pittsburgh.

Collins, J., and Sadeh, N. (eds.), 2009. Special Section: Supply Chain Trading Agent Research. *Electronic Commerce Research and Applications*, 8 (2), 59-114.

De Snoo, C., Wortmann, J.C., Gaalman, G.J.C., and Van Wezel, W., 2007. Decomposition of the planning function implies coordination of planners. In *Proc of* EurOMA'07.

Fleish, E., 2010. What is the Internet of Things? Auto-ID Labs White Paper WP-BIZAPP-05, University of St. Gallen.

Galbraith, J., 1973. Designing complex organizations, Addison Wesley, Boston.

Gerding, E.H. (ed.), 2009. Proceedings of the 7th International Workshop on Trading Agent Design and Analysis.

Gershenfeld, N., 2000. When Things Start to Think. Owl books, New York.

Gershenfeld, N., Krikorian, R., Cohen, D., 2004. The internet of things, Scientific American 291 (4), 76-81.

Herrmann, J.W., 2006. *Handbook of Production Scheduling*. New York, Springer.

Hribernik, H.A., Rabe, L., Thoben, K-D., and Schumacher, J., 2006. The product avatar as a product-instance-centric information management concept. *Product Lifecycle Management*, 1 (4), 367-379.

Huvio, E., Grönvall, J., and Främling, K., 2002. Tracking and tracing parcels using a distributed computing approach. In *Proc. of NOFOMA'02*, 29-43.

Jammes, F., and Smit, H., 2005. Service-Oriented Paradigms in Industrial Automation. In *Proc. of IASTED'05*, 716-723.

Jordan, P.R., Kiekintveld, C., Miller, J., and Wellman, M.P., 2007. Market efficiency, sales competition, and the bullwhip effect in the tac scm tournaments. *LNCS*, 4452, 62-74.

Kiekintveld, C., Miller, J., Jordan, P.R., and Wellman, M.P., 2006. Controlling a supply chain agent using value-based decomposition. In *Proc. of ACM conf. on EC'06*, 208-217.

Lindau, R.A., and Lumsden, K.R., 1995. Actions taken to prevent the propagation of disturbances in manufacturing systems. *International Journal of Production Economics*, 41 (1-3), 241-248.

McKay, K.N., and Wiers, V.C.S., 2006. The Organizational Interconnectivity of Planning and Scheduling. In: Van Wezel, W., Jorna, R.J., and Meystel, A.M. (eds.) *Planning in Intelligent Systems: Aspects, Motivations, and Methods.* New York: Wiley, 177-201.

McCullen, P., and Towill, D., 2002. Diagnosis and reduction of bullwhip in supply chains. *Supply Chain Management: An International Journal*, 7 (3), 164-179.

McFarlane, D., Sarma, S., Chirn, J.L., Wong, C.Y., and Ashton, K., 2003. Auto id systems and intelligent manufacturing control. *Engineering Applications of Artificial Intelligence*, 16 (4), 365-376.

Meyer, G.G., Främling, K., and Holmström, J., 2009. Intelligent products: A survey. *Computers in Industry*, 60 (3), 137-148.

Meyer, G.G., and Wortmann, J.C., 2010. Robust Planning and Control using Intelligent Products. *LNBIP*, 59, 163-177.

Mesarovic, M.D., Macko, D., and Takahara, Y., 1970. Theory of hierarchical,multilevel, systems. Academic Press, New York.

Orlicky, J., 1975. *Material Requirements Planning*. McGraw-Hill, New York.

Pardoe, D., and Stone, P., 2004. Tactex-03: A supply chain management agent. *SIGecom Exchanges: Special Issue on Trading Agent Design and Analysis*, 4 (3),19-28.

Pardoe, D., Stone, P., and VanMiddlesworth, M., 2007. Tactex-05: An adaptive agent for tac scm. *LNCS*, 4452, 46-61.

Pinedo, M.L. Scheduling: Theory, Algorithms, and Systems, 3 ed. New York: Springer 2008.

Roest, G.B., and Szirbik, N.B., 2009. Escape and intervention in multi-agent systems. *AI & Society*, 24 (1), 25-34.

Rönkkö, M., Kärkkäinen, M., and Holmström, J. , 2007. Benefits of an item-centric enterprise-data model in logistics services: A case study. *Computers in Industry*, 58(8-9), 814-822.

Saad, A., Kawamura, K., and Biswas, G., 1995. Performance evaluation of contract net-based heterarchical scheduling for flexible manufacturing systems. In *Proc. of IJCAI'95*, 310-321.

Schneeweiss, C., 2004. *Distributed Decision Making*, Springer, Berlin.

Shen, W., Hao, Q., Yoon, H.J., and Norrie, D.H., 2006. Applications of agent-based systems in intelligent manufacturing: an updated review. *Advanced Engineering Informatics*, 20 (4), 415-431.

Slack, N., Chambers, S., and Johnston, R., 2004. *Operations management*. Pearson Education.

Smith, R.G., 1980. The Contract Net Protocol: High-Level Communication and Control in a Distributed Problem Solver. *IEEE Transactions on Computers*, C-29 (12), 1104-1113.

Stan, M., Stan, B., and. Florea, A.M., 2006. A dynamic strategy agent for supply chain management. In *Proc. of SYNASC'06*, 227-232.

Strassner, M., and Schoch, T., 2002. Todays impact of ubiquitous computing on business processes. In *Proc. of Pervasive'02*, 62–74.

Taisch, M., Colombo, A.W., Karnouskos, S., and Cannata, A., 2006. SOCRADES Road map – The Future of SOA-based Factory Automation. Available at: www.socrades.eu.

Toulis, P., Kehagias, D., and Mitkas, P.A., 2006. Mertacor: a successful autonomous trading agent. In *Proc. of AAMAS'06*, 1191-1198.

Töyrylä, I., 1999. *Realising the potential of traceability*. PhD thesis, Helsinki University of Technology.

Van Leeuwen, E.H., and Norrie, D.H., 1997. Holons and holarchies. *Manufacturing Engineer*, 76 (2), 86-88.

Van Wezel, W., Van Donk, D.P., and Gaalman, G.J.C., 2006. The Planning Flexibility Bottleneck in Food Processing Industries, *Operations Management*, 24 (3), 287-300.

Venkateswaran, J., Zhao, X., and Son, Y.J., 2003. Intelligent shop floor scheduling method considering realtime status, disturbances, and performance metrics. *In Proc. of IJIE'03*.

Vieira, G.E., Herrmann, J.W., and Lin, E., 2003. Rescheduling Manufacturing Systems: A Framework of Strategies, Policies, and Methods, *Journal of Scheduling*, 6 (1), 39-62.

Wong, C.Y., McFarlane, D., Zaharudin, A., and Agarwal, V., 2002. The intelligent product driven supply chain. In *Proc. of SMC'02*.

Wortmann, J.C., Euwe, M.J., Taal, M., and Wiers, V.C.S, 1996. A review of capacity planning techniques within standad software packages. *International journal of Production Planning and Control*, 7 (2), 117-128.

Figures