Intelligent Products in the Supply Chain
Are Merging Logistic and Manufacturing Operations
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Abstract: The control of a supply chain becomes more and more complex. The actions and operations of the different parties need to be coordinated in order to control the supply chain in an efficient way. The concept of ‘Intelligent Product’ can play an important role in this challenge. The intelligent product searches actively for the needed services offered by (intelligent) resources. The Holonic Manufacturing Execution System developed at K.U.Leuven makes use of this concept to control the internal logistics of a manufacturing system. Because of the active role of the intelligent products, the HMES is scalable and can coordinate beyond organizational boundaries. The paper explains the intelligent product concept and indicates the advantages of this approach by describing how a cross-dock can be controlled and integration with the inbound and outbound vehicles can be achieved.

Keywords: Holonic manufacturing control, intelligent product, intelligent cargo, cross-docking, self-organizing systems

1. INTRODUCTION

It is generally accepted that supply chain management has become more and more complex. Reasons are globalization, the markets that become customer-driven (smaller volumes of customized products, shorter product life cycles), the implementation of manufacturing strategies like just-in-time and lean manufacturing, etc. From an operational point of view, the actions and operations of the different parties need to be coordinated in order to control the supply chain in an efficient way. Because the supply chain is a dynamic environment, it is also important to be able to deal with disturbances and unexpected events.

Production can be seen as a part of the supply chain. To control the production, a production manager can be supported by a Manufacturing Execution System (MES). For several years now, researchers of the Department of Mechanical Engineering at K.U.Leuven are working on a MES that handles the internal logistics in a manufacturing system. The system makes use of a holonic, self-organizing and decentralized approach. This Holonic MES or HMES tries to improve the responsiveness, proactiveness, scalability and flexibility of the system and handles changes and disturbances as business-as-usual (Valckenaers and Van Brussel [2005]).

The concepts and principles of this approach can be applied in the larger context of the supply chain. At present, research has started to develop a Holonic Logistic Execution System (HLES) by applying the same principles as used in the HMES to transport and logistics. Real benefits are expected when HMES and HLES are integrated and are able to interact with each other. This integration is possible because of the scalability of both systems. The scalability results from the use of ‘Intelligent Products’. These intelligent products are capable of communicating with the environment and make decisions relevant for their own destiny (e.g. routing through the system). This paper explains the role of the intelligent products in the HMES and indicates how these intelligent products enable the extension from production to supply chain. An example of the holonic control of a cross-dock together with the inbound and outbound vehicles will illustrate some advantages of this approach.

In the next section, some existing literature about the intelligent product concept is described. Next, the Holonic Manufacturing Execution System is explained and how the intelligent product concept is used in the HMES. To clarify the extensibility of this approach, an example is given on how a cross-docking terminal is controlled and how the control of the vehicles can be integrated. In the last section, conclusions are drawn.

2. INTELLIGENT PRODUCTS

Wong et al. [2002] define an intelligent product as follows. An intelligent product:

(1) Possesses a unique identity
(2) Is capable of communicating effectively with its environment
(3) Can retain or store data about itself
(4) Deploys a language to display its features, production requirements, etc.
(5) Is capable of participating in or making decisions relevant to its own destiny

Based on this definition, the authors see a distinction between two levels of ‘intelligence’. The first level allows a product to communicate its status, i.e. information oriented. This corresponds to points 1 to 3 of the proposed definition. The second level allows a product to assess and influence its function in addition to communicating its status, i.e. decision oriented. Level two therefore covers points 1 to 5.

Other definitions are given by Kärkkäinen et al. [2003] and Ventä [2007].

Intelligent products can be classified according to the level of intelligence, the location of intelligence and the aggregation level of intelligence (Meyer et al. [2009]). The authors also discuss some technologies that (will) enable the intelligent product concept. Some application domains are manufacturing, supply chains, asset management and product life cycle management.

Valckeniers and Van Brussel [2008] and Valckeniers et al. [2009] describe an intelligent product as the combination of an intelligent agent and an intelligent being. The intelligent being reflects the corresponding real product and is restricted to provide functionality and services for which the corresponding reality provides adequate protection: any functionality or service that requires decision-making, not imposed by reality, is delegated to the intelligent agent.

In the context of transport logistics, the term ‘intelligent cargo’ is also used (e.g. the EURIDICE EU project [Eur [2010]])). Intelligent cargo is a concept that has the potential to offer high-quality logistic services. The KP7 project EURIDICE (about 1600 man-months, duration 3 years) studies and develops this technology. The goal is to have a paradigm shift towards the intelligent cargo concept in the field of ICT applications for transport logistics. According to the project (Paganelli et al. [2009]), “Intelligent Cargo connects itself to logistics service providers, industrial users and authorities to exchange transport-related information and perform specific services whenever required along the transport chain”. The vision of the project is the following: “In five years time, most of the goods flowing through European freight corridors will be ‘intelligent’, i.e.: self-aware, context-aware and connected through a global telecommunication network to support a wide range of information services for logistic operators, industrial users and public authorities”. The EURIDICE project recognizes autonomous decisions as the most advanced level for intelligent cargo. Intelligent cargo will autonomously execute the necessary actions in function of the current circumstances and opportunities.

3. HOLONIC MANUFACTURING EXECUTION SYSTEM

3.1 Overview

A Manufacturing Execution System or MES coordinates and controls the manufacturing system. Manufacturing control is the operational level of production planning and control and is concerned with the short-term and detailed assignment of operations to production resources (Verstraete et al. [2007]). Due to the nonlinear nature of the production environment, the uncertainties stemming from the production processes and the combinatorial growth of the decision space, this is a daunting task (Valckeniers and Van Brussel [2005]).

The Holonic MES or HMES developed at K.U.Leuven is based on the PROSA reference architecture (Van Brussel et al. [1998]). This architecture describes the structure of the software: the components, their responsibilities and their interactions. The PROSA architecture is developed in accordance with the holonic manufacturing paradigm (see e.g. Van Brussel et al. [1998], McFarlane and Bussmann [2000], Babiceanu and Chen [2006], Monostori and Kádár [1998], Leitão [2000]). Holonic architectures were introduced to provide an answer to some shortcomings in existing manufacturing control architectures (e.g. centralized, hierarchical and heterarchical architectures) (Babiceanu and Chen [2006], Verstraete et al. [2007]). Holonic architectures try to combine the high and predictable performance promised by hierarchical systems with the robustness against disturbances and the agility of heterarchical systems by having characteristics of both architectures.

The next section describes the functioning of the HMES and the important role of the intelligent product.

3.2 Intelligent products in HMES

An important issue in the intelligent product concept is that the products can take autonomous decisions. This is also the case for the HMES, and moreover, the intelligent products can make use of short-term forecasts to improve their decisions. The generation of short-term forecasts is made possible by the interaction between the intelligent products and the intelligent resources.

The intelligent products are a combination of an intelligent agent and an intelligent being (Valckeniers and Van Brussel [2008], Valckeniers et al. [2009]). The intelligent agent is responsible for decision-making and achieving objectives, the intelligent being reflects the corresponding product instance. Similarly, the intelligent resources consist of an intelligent agent and an intelligent being. The intelligent agent takes (local) decisions about the resource, while the intelligent being reflects the corresponding resource in the real world. Moreover, the intelligent resources are equipped with a reservations service, like hotels, that can answer queries about the kind of services their resource may deliver and the availability of these services over time.

The interaction between the intelligent products and resources is inspired by ant colony behavior (Valckeniers and Van Brussel [2005]). The intelligent products create at regular intervals a lightweight agent - a so-called ant agent - that can travel virtually through the network formed by the intelligent resources. There are two types of ant agents: exploring and intention ant agents. The exploring ants execute virtually a single possible journey through the network that would result in the correct production of the product. During this virtual journey, the ant agent collects information about resource capabilities and availability by querying the reservation service of the
intelligent resources. No reservations are made yet. The intelligent order then evaluates the different solutions of the exploring ant agents and chooses one to become its intention by sending an intention ant agent. This intention ant virtually executes the chosen journey and reserves the necessary capacity with the involved intelligent resources. In this way, the intelligent products know the expected itineraries/routings for the products and the intelligent resources know the predicted loads/allocations for the resources. These short-term forecasts can then be used by the agents to improve their decision-making capabilities. Note that both types of ant agents are created regularly so that the intelligent product can react to disturbances and new opportunities.

The scalability of the system is a result of the active role of the intelligent product. It is the intelligent products who actively search for the services they need and continuously seek alternatives. If only the intelligent resources could take the initiative, then any new type of task would require training for the intelligent resources. Because of the presence of the intelligent products, the resources can limit themselves to the provision of services. So the resources stay free of maintenance as long as the corresponding resource remains unchanged. For instance, if new resources become available, it suffices to add the corresponding intelligent resources. The intelligent product will detect these new resources during exploring and can decide to make use of the new available resources (which offer already available or new services). The behavior of the intelligent product does not have to change, it keeps sending out ant agents to find a suitable routing. In the same way, the system can be extended beyond its borders. For instance, for a manufacturing system, the transportation can also be considered if there are intelligent resources available for the different transportation means. The role of the intelligent product is still the same. It has to search a journey through the system, but now this journey should also include the transportation operations. So, the intelligent product allows to integrate the subsystems responsible for manufacturing and transportation.

The use of the intelligent products makes the system scalable and allows the generation of short-term forecasts which on their turn allow to improve the local decision making. The next section describes cross-docking and the use of intelligent products. The scalability and integration will be illustrated by means of some example scenarios.

4. INTELLIGENT PRODUCTS IN CROSS-DOCKING

4.1 Cross-docking

Cross-docking is a logistics strategy nowadays used by many firms in different industries (e.g. retail firms and less-than-truckload (LTL) logistics providers). Cross-docking can be described as the process of unloading freight from an inbound truck and loading these goods directly into outbound trucks, with little or no storage in between. If the goods are temporarily stored, this should be only for a short period of a time. An exact boundary is difficult to define, but many authors talk about 24 hours. This leads to shorter delivery lead times and corresponds with the goals of lean supply chain management: smaller volumes of more visible inventories that are delivered faster and more frequently. Another goal of cross-docking is consolidation of shipments, which is also an advantage if there are more (but smaller) volumes to ship.

A terminal dedicated for cross-docking is called a cross-dock. In practice, most cross-docks are long, narrow rectangles (I-shape), but other shapes are also used (L, T, X, . . .). A cross-dock has multiple loading docks (or dock doors) where trucks can dock to be loaded or unloaded. Incoming trucks are assigned to a ‘strip door’ where the freight is unloaded. Then the goods are moved to their appropriate ‘stack door’ and loaded on an outbound truck. Fig. 1 presents a schematic representation of the material handling operations at an I-shaped cross-dock with 10 dock doors. Incoming trucks are either directly assigned to a strip door or have to wait in a queue until assignment. Once docked, the freight (e.g. pallets, packages or boxes) of the inbound trailer is unloaded and the destination is identified (e.g. by scanning the barcodes attached to the goods). Then, the goods are transported to the designated stack door by some material handling device, such as a worker operating a fork lift or some kind of conveyor belt system. There, the goods are loaded onto an outbound truck that serves the dedicated destination. Once an inbound truck is completely unloaded or an outbound truck is completely loaded, the truck is replaced by another truck.

The operations in a cross-dock are typically seen as logistics operations. However, in several cases extra (value-added) activities are performed on the goods, for instance repacking or labeling. In these cases the cross-dock can be considered as a (non-trivial) production environment.

Different problems concerning cross-docking are studied in literature. These problems can be divided on the one hand in tactical problems and on the other hand in operational problems. Tactical problems that are considered are the location of the cross-dock (or cross-docks) (Gümmüs and Bookbinder [2004], Ross and Jayaraman [2008]) and the layout of the cross-docking terminal (Bartholdi III and Gue [2004]). Operational problems tackled in literature are about the assignment of trucks to dock doors (Tsui and Chang [1990], Bartholdi III and Gue [2000], Boysen and Fliedner [2010]), the location where goods will be temporarily stored (Vis and Roodbergen [2008]) and vehicle routing (Lee et al. [2006]). Some authors also consider...
operational issues at the network level and try to optimize
the flow of goods through a network of cross-docks (Lim
et al. [2005], Chen et al. [2006]).

4.2 HMES and cross-docking

The concepts and principles of the HMES can be used to
control the operations in a cross-dock. The basic idea of
the HMES is to reflect all relevant entities of the world-
of-interest by software entities. There are two important
types of entities: resources and products. Both types are
responsible for their own (local) decisions.

First of all, the entities that can be seen as resources will
be represented by an intelligent resource. In the context
of cross-docking, this means that for instance all trucks,
forklifts and dock doors will have a software counterpart.
These intelligent resources contain a model of the dynamic
behavior of the corresponding resource so that what-if
questions can be answered. Next to reflecting the real
entity, the software entities are also responsible for their
own local decisions (e.g. a dock door should decide which
truck it handles). This decision making can be seen as a
plug-in to the system and can be easily replaced by another
algorithm/rule. The decisions can be based on previously
taken decisions which form a schedule with the orders that
will be processed in the near future.

Secondly, the products will also be represented by a soft-
ware entity. In cross-docking, products correspond to the
freight units that are transported, e.g. pallets. This prod-
uct software entity fulfills the role of the intelligent product
as discussed in the previous section. It is responsible for
routing its corresponding entity of the real world through
the cross-docking system. Through interaction with the
available resource entities, the intelligent product will
schedule the necessary operations to process the product
instance. In the context of cross-docking, the typical oper-
ations a product instance has to reserve are: the unloading
from an inbound truck, the transportation to temporary
storage, the storage itself and the loading operation into
an outbound truck.

When the necessary models for the trucks are developed,
the ant agents do not need to stop at the borders of the
cross dock system, but they are able to visit the trucks in
a virtual way. For instance, the intelligent product
corresponding to incoming cargo sends out ant agents that
virtually travel to the cross-dock. In this way, they keep
the cross-docking terminal continuously informed about
their expected arrival. By doing so, every variation in
arrival time becomes known including the consequences.
Dependent on this, the intelligent product can decide to
keep its intention or to adapt its intention. The other way
around, an incoming truck sees the predicted congestion
at its expected arrival time. Ant agents can then discover
alternative solutions in which the incoming truck for
instance first refuels or introduces a break for the driver
before delivering the goods.

In a similar way, the coordination through the help of the
ant agents can be extended further, for instance when the
goods are delivered from a manufacturing system. In this
case, the manufacturing system can be integrated with the
transport and cross-docking system and the ant agents

![Fig. 2. The outbound truck at dock 8 has to wait for the
inbound truck scheduled at dock 9.](image)

travel through all 3 systems. It should be noted that it
is not necessary to disclose the internal functioning of a
subsystem to the outside world. It is sufficient to reveal
the end result of the virtual execution.

4.3 Example scenarios

To clarify the advantage of the integration of different
systems by means of intelligent products and how the local
decisions of the intelligent products and resources can be
improved by the availability of short-term forecasts, some
example scenarios are described.

Dock door assignment. The problem of dock door as-
signment focuses on the ‘optimal’ assignment of inbound
and outbound trucks to dock doors (e.g. to minimize
the travel distance of the freight inside the cross-dock).
Suppose now an outbound truck (the truck at dock 8
in Fig. 2) cannot leave because it still needs to load
freight from a belated inbound truck. This inbound
truck is assigned by the scheduling system to dock 9,
next to the outbound truck. Dock 8 and 9 are docks
with a central position, so with the smallest average
distance to all other doors. It is therefore profitable
that these docks have a high throughput. Typically, the
schedule system will take this into account. Figure 3
shows an exemplary schedule where the central docks 3,
4, 8 and 9 have a high capacity utilization. If there is
no coordination between the cross-dock control system
and the transportation control system, the outbound
truck will wait until the belated inbound truck arrives.
This causes all scheduled operations at dock doors 8
and 9 to shift forward in time (see Fig. 4) or these
operations have to be rescheduled at other docks. In
both cases, dock 8 and 9 are occupied unnecessarily
until the belated truck arrives. This can have a serious
impact on the throughput if the delay of the inbound
truck is significant. When there is coordination between
the two systems by means of the intelligent product, the
intelligent resource corresponding to the dock doors (an
aggregated resource) will be warned about the delay.
Then, the intelligent resource decides for instance to as-
sign the inbound and outbound trucks to less centralized
dock doors (e.g dock doors 1 and 2) if the unloading did
not start yet. The intelligent resource can also make
use of the available short-term forecasts. It knows the
delay of the inbound truck and the expected arrival times and (un)load times of other trucks. Based on this information, the intelligent resource assigns for instance another truck to dock 9 if this truck will be finished before the arrival of the belated truck (see Fig. 5). In this way, the centralized dock doors are used more efficiently. This adaptation is maybe not the most ‘optimal’ one (that e.g. can be obtained with complete rescheduling), but it shows that it is advantageous to be able to take informed decisions.

**Batching in outbound trucks.** Typically, freight arriving at a cross-dock is dedicated to a certain outbound truck. The outbound truck leaves if all goods are loaded. Suppose however that one pallet is missing because the inbound truck is stuck in a traffic jam. Because of this, the outbound truck and all products that are already loaded have to wait and will probably miss their due date. In the HMES approach, the intelligent resource corresponding to the outbound truck decides if it is better to wait for the missing product or if it is better to leave without. If no short-term forecasts are available, the intelligent resource is myopic and it is difficult to make a deliberate choice. If the intelligent resource knows the expected arrival time of the missing product and other trucks with the same destination, the resource has the necessary information to take a well-considered decision.

**Congestion at the cross-dock.** When many inbound trucks arrive at the same time at the cross-dock, not all trucks can be handled simultaneously and some have to wait until a dock door becomes free. For the waiting trucks and drivers, this means a waste of time. By means of the short-term forecasts generated by the intelligent products, it would be possible for the truck to foresee this waiting time and react in a more advantageous way. For instance, the driver can make a small detour to already refuel its truck on its way to the cross-dock. Or the driver can already take some rest in order to avoid troubles with driving hours later on.

5. CONCLUSION

The Holonic Manufacturing Execution System developed at K.U.Leuven handles the internal logistics of a factory. It assigns operations to production resources and has to deal with changes and disturbances. An important role in the HMES is reserved for the intelligent product. The intelligent product searches actively for the needed services offered by the resources. These (intelligent) resources can limit themselves to the provision of services, which makes it a stable component of the software. As long as the corresponding resource does not change, the intelligent resource can remain unchanged.

Because of the active role of the intelligent product, it is possible to extend the system, e.g. to transport and logistics. Real benefits are expected when both systems can be integrated. The examples in section 4.3 tried to indicate the possible advantages when two control systems (for the cross-dock and the trucks) cooperate by means of the intelligent products. Currently, in cooperation with industry, research has started to develop a proof of concept to show that these advantages can indeed be obtained.

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