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Jan R. Nopper
Fraunhofer-Institute for Material Flow and Logistics

Guido Follert
Fraunhofer-Institute for Material Flow and Logistics

Michael ten Hompel
Fraunhofer-Institute for Material Flow and Logistics

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Jan R. Nopper   Guido Follert   Michael ten Hompel

Fraunhofer-Institute for Material Flow and Logistics, Dortmund

Abstract

Compared to conventional material flow controls, self-organized material handling systems and the Internet of Things in facility logistics promise several advantages during the life-cycle. Most important is the increased adaptability in case of expansions or modifications due to a consistent modular design; this also promotes an increased robustness due to clearly defined interfaces and a decreased complexity of each module. The use of RFID technology increases the availability of real-time data about the system and the transported units. However, the introduction of self-organized material handling systems also causes costs, e.g. for necessary RFID tags and readers. Against this background, it is unsatisfactory that the increased adaptability as the main advantage of these systems is hard to grasp. This paper proposes a methodology to analyze the advantages of adaptability in facility logistics during the life-cycle of a material handling system and illustrates its usage. The proposed methodology is based on a dynamic optimization of payoffs during the life-cycle; thereby, all payoffs which are influenced by the adaptability of the material-handling system are included; therefore, the methodology allows to consider the adaptability of all material handling systems.

Keywords: Internet of Things, Self-Organization, Facility Logistics, Adaptable Material Handling Systems, Operations Research, Dynamic Optimization, Life-Cycle Costs.

1   Introduction

Self-organized material handling systems[1] represent a consistent decentralization approach of the material flow control. They are based on the developments of Radio Frequency Identification (RFID), which allow to build material handling systems without any central control. Instead, the necessary data travels with the transport unit; material and information flow are directly connected (cp. [1]).

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[1] Self-organized systems in facility logistics represent one possible domain for the Internet of Things.

The basic idea of self-organization in logistics is to split the conventional central material flow control into many independent control units. All logistical objects–especially conveyors and loads–are represented by software agents, which are able to communicate with the agents of other objects. All objects may offer or demand specific services; for instance, a pallet might ask for the transport from one location to another and the transport might be offered by two AGV. Then, the software agent of the pallet chooses one of the transport offers by comparing them with its specific requirements. The total system function is achieved by setting the goals and parameters of the agents accordingly; with that, they act independently within a multi-agent system. The software agents representing the materials handling equipment can run directly at the decentral control units. Usually, it is not reasonable to equip every load with a separate control unit for the corresponding software agent (*Agent-on-Tag concept*). Instead, only an unique identification could be attached to every load[2] that refers to an agent running on another and possibly central hardware (*ID-on-Tag concept*). If RFID tags with sufficient storage space are used, the structure, the status, and all parameters of the agent can be stored on the tag (*Data-on-Tag concept*). Here, necessary calculations are performed on the computer hardware of close-by entities, e.g., on that of a used conveyor. This concept has advantages regarding the communication effort and robustness when compared to the *ID-on-Tag* concept.

Thus, self-organization allows a complete modularization of the material handling system. Every module has consistent interfaces to neighboring modules, which are identical for mechanical and electrical installations as well as the control represented by a software agent (cp. [2], [3], [4], [5]). This approach promises many advantages, especially the possibility to change and extend the system with very low effort ('Plug&Play', cp. [6]) thus leading to a higher adaptability. However, to date exists no suitable quantification method for the adaptability of material handling systems. It is the aim of this work to develop such a methodology which is especially suited for self-organized material handling systems.

The remainder of the paper is organized as follows. Based on current literature, section 2 gives an overview of expected advantages of self-organized material handling systems. Section 3 reviews existing methods to quantify flexibility and adaptability in material handling systems shortly; based on that, a suited methodology to quantify adaptability in self-organized material handling systems is proposed. The application of this methodology is explained in section 4 by analyzing an illustrative example.

2 Advantages of self-organized material handling systems

Self-organized material handling systems may cause higher costs than conventional systems in some aspects. For instance, they may increase operating costs due to necessary

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[2] This can be done either with bar-code or RFID tags.

RFID tags or the modular approach may increase capital expenses in some cases. Usually, increased costs are rather simple to quantify. On the other hand, self-organized material handling systems show significant advantages over their life-cycle. In the literature, three main advantages are discussed:

- Increased flexibility/adaptability regarding expansions or modifications of the system (e.g. [7], [1], [8], [9], [10], [2], [6]).

- Increased robustness against environmental disturbances (e.g. [7], [1], [8], [9], [2]).

- Increased availability of information about system elements and transported units (e.g. [11], [12]).

We discuss these aspects in the following; also, we explain possible effects on the logistical performance shortly (cp. [13]).

The **logistical performance** usually is measured by the parameters throughput, throughput time, work-in-progress, utilization rates and schedule reliability [14]. Their relative importance depends on the considered application. There is some evidence, however, that self-organization does not change the logistical performance itself significantly. [15] and [16] analyze conventional and decentral control strategies for order picking applications. They find very similar results for both strategies regarding throughput, throughput time, and utilization rates. In another example, [2] show with the help of an extensive simulation study that throughput times of an agent-based decentral control are comparable to those of conventional baggage handling systems in a major airport environment. These results are in line with expectations as in theory any central control algorithm can be decentralized. Therefore, we expect no major performance differences between self-organized and conventional material handling systems.

On the contrary, the modular design of such systems will increase the **flexibility and adaptability** of such systems considerably in the opinion of many scholars. A comprehensive modularization of mechanics, electrical drives, communication technology, and control into consistent modules allows a fast and simple expansion and modification of the material handling system. The functionality of such systems was already proven: For instance, [6] build a modular steady conveyor system where the single modules can be connected via *Plug&Play*. In fact, the increased adaptability is one of the most promising aspects of self-organized material handling systems.

Robustness in material handling systems is often defined as the completeness of description of possible environmental states and inputs to the system (cp. [17]). Therefore, robustness of a system is increased by the amount of potential critical situations described within its control. Such situations can be analyzed along the

dimensions *information and operation* (e.g., a transported unit cannot be identified), *conveyed goods* (e.g., a transported unit is too big) and *environmental conditions* (e.g., the humidity is higher than specified) [18]. The completeness of description can be improved significantly by decentralization as the modular approach allows the formulation of shorter algorithms and increase clarity of programs. For instance, [2] show that a baggage handling system of a major airport can be controlled decentrally with a code ten times shorter than that of conventional controls.

Finally, the use of RFID tags in self-organized systems increases the availability of information. [11] suggest to analyze potential advantages within three categories:

- *process level*, e.g. simplified stock taking,

- *network level*, e.g. less out-of-stock situations,

- *additional services*, e.g. real time information for customers.

However, most of these advantages of self-organized systems are difficult to quantify today. This is especially true for flexibility and adaptability as the main advantage of such systems. This is unsatisfactory; therefore, we developed a method to quantify advantages of self-organized systems, which is especially suited to quantify economic effects of a higher adaptability.

3   A methodology to quantify adaptability in facility logistics

As explained, there exists no suited methodology to quantify adaptability in facility logistics in monetary terms. Furthermore, many different dimensions and flexibility types are discussed in the literature (cp. for example [19] or [20]). However, [21] propose that only three flexibility types are relevant for material handling systems: layout flexibility, throughput flexibility, and the flexibility regarding the material to be conveyed.

Now assume that the state of the system for each point in time can be described by a vector $x(t)$; thereby, all components of x have to be linearly independent and x should only contain state variables which are likely to change in the life-cycle. If - for instance - the state of a continuous conveyor system can be described by the number of sources, the number of sinks, the total length of the conveyors, and the number of loading devices, x would be four-dimensional. If in a real application the number of sources and sinks is only dependent on the length of the conveyor system and if the number of different loading devices is not expected to change in the life-cycle, x would be one dimensional.

With this, all costs in the life-cycle caused by operation, modification and expansion of the material handling system can be described in terms of the actual system state $x_A(t)$, the required system state $x_B(t)$, and the change in system size $u(t) = \Delta x_A(t)$ for all times t. Often, the relevant cost components are the investment costs $I(u)$, the operating

expenses $O(x_A)$, and congestion costs $C(x_A)$. The last accrue when the actual system 'size' $x_A(t)$ is 'smaller' than the required system 'size' $x_B(t)$. If the net present value NPV_{LC} of all payoffs due to these cost components is considered, the following optimization problem can be formulated:

$$NPV_{LC} = \sum_{j=1}^{N} e^{-r_j \cdot t_j} \cdot \left[I(u_j) + C(x_{A,j}, x_{B,j}) + O(x_{A,j}) \right] \rightarrow min \qquad (1)$$
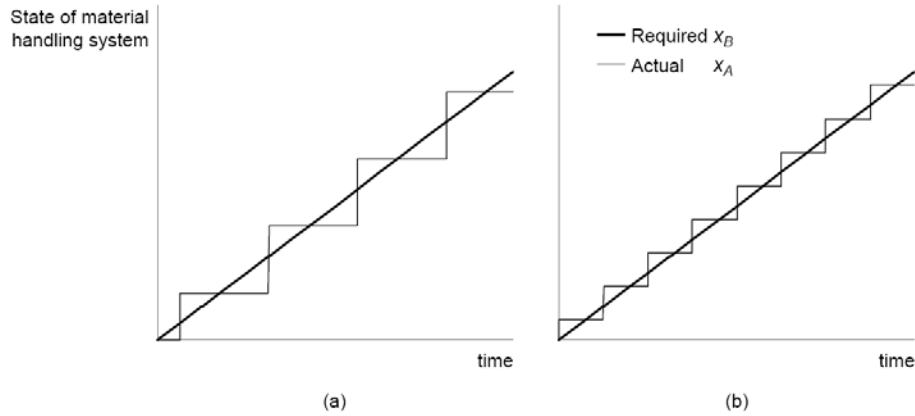
s.t.

$$x_{A,j} = f(x_{A,j-1}, u_j) = x_{A,j-1} + u_j \qquad (2)$$

$$x_{A,0} = given \qquad (3)$$

$$x_{A,j} \in \Xi_j \qquad (4)$$

$$u_j \in \Omega_j(x_{A,j-1}) \qquad (5)$$

Here, N denotes the number of considered periods, r_j is the interest rate in period j, t_j is the time in period j. This optimization problem is similar to capacity expansion problems (cp. [22], [23]) and can be solved by dynamic programming (cp. [24]).

Figure 1 : Adaptation of maximum system size to demand for one dimensional x.
   (a) – Less adaptable system,
   (b) - More adaptable system.

  Figure 1 illustrates the resulting changes in x_A in dependency of the system adaptability for a one dimensional problem and a known future. A more adaptable system results in smaller adaptation steps - x_A follows x_B closer for a more adaptable system, thus decreasing operating costs and congestion costs directly. Furthermore, the more adaptable system allows on average later times of investment; this leads to lower

discounted investment. Finally, a more adaptable system provides an 'insurance against uncertainty' in case of unknown x_B as smaller adaptation steps allow a later decision.

4 Illustrative Example

In the following, the use of the proposed methodology for an analysis of adaptability in facility logistics is explained. Consider equation (1) with $t_j = (j-1) \cdot \Delta t$ and one-dimensional x with

$$I = \begin{cases} FI + u_j \cdot \sigma & for \ u_j > 0 \\ 0 & for \ u_j = 0 \end{cases} \tag{6}$$

$$O = \beta \cdot x_{A,j} \cdot \sigma \cdot \Delta t \tag{7}$$

$$C = \begin{cases} \delta \cdot (x_{Bj} - x_{A,j}) \cdot \Delta t & for \ x_{A,j} < x_{B,j} \\ 0 & for \ x_{A,j} \geq x_{B,j} \end{cases} \tag{8}$$

and

$$x_{A,t=0} = x_{B,t=0} \tag{9}$$

x_B shall be growing linearly over time:

$$x_{B,j} = g + h \cdot t_j \tag{10}$$

In this case, the adaptability of a material handling system is dependent on the value of FI which are the fixed investment costs; they have to be paid regardless of the size of an adaptation of the system. Obviously, the system is more adaptable if FI is smaller. In practice, FI consists mainly of necessary programming and configuration of material flow control which has to be done for every adaptation of the system. It is obvious, that a Plug&Play functionality may decrease FI significantly.

Consider for example an automated guide vehicle system (AGV) for a production plant with a life-cycle of 20 years. Furthermore, assume an interest rate of $r_j = 0.1$, a linearly growing, known production output of 0 pieces per day at $t = 0$ years and 1, 000 pieces a day at $t = 20$ years, a transport capacity per vehicle of 100 pieces a day, variable investment costs of 100,000 USD per vehicle, operating expenses of 15,000 USD per vehicle and year, 200 workdays per year and congestion costs of 5 USD per piece which cannot be transported by the AGV. If every system adaptation costs $FI_{\text{inadapt}} = 100{,}000$ USD for a less adaptable system and $FI_{\text{adapt}} = 30{,}000$ USD for a more adaptable system, one finds a difference in NPV between both systems of about 200,000 USD respectively 16 per cent (see figure 2).
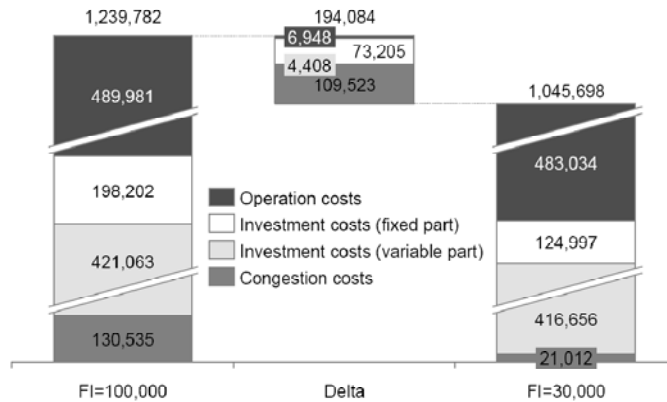
Figure 2 : Differences in discounted life-cycle costs for the illustrative example.

It is interesting to note that the main difference is not the investment costs but the congestion costs. Furthermore, an increased adaptability decreases all cost components in this case.

5   Conclusion and outlook

This paper analyses increased adaptability as the main advantage of self-organized material handling systems. A method for analyzing and quantifying adaptability in monetary terms is proposed and explained.

This method will be elaborated further in future; especially the relationship of adaptability and an unknown future will be explored. Furthermore, the methodology will be used to analyze practical examples from facility logistics.

One interesting field of application is the Hub2Move concept which is currently being developed at Fraunhofer Institute for Material Flow and Logistics in Dortmund: With today's volatile markets and global supply chains there should be a coherent demand for adaptable distribution warehouses and transshipment nodes, shortly called hubs. Material-handling systems used in those hubs must be adaptable to changing requirements, effortlessly movable to other locations and brought back to operation in short time. Today, hubs are designed as stationary units that have inside a fixed configuration of handling and storage technology with a useful life of 15 years.

The expression Move in the acronym Hub2Move stands for the objective of the concept. It is the prospective adaptability of the new hubs, both in terms of their geographical arrangement as well as their changing functional performance in logistics networks. In future the arrangement and the configuration of the hubs are central adjusting lever of short-and medium-term logistics planning. They enable efficiencies in

supply chains through demand-driven arrangement of the hubs - synchronously with the medium-term distribution network planning every few years - or through the modification of internal structures and processes as the basis of a continuous improvement process. A joint research project provides the basic concepts for the Hub2Move incorporating technical elements and controls for its implementation. Industrial partners are contributing to the work on machinery and simulation of the new technology. The functions of a Hub2Move must be adaptable and an entire terminal node must be running within a few weeks at a new location, such as Siemens has already impressively demonstrated for the function of a single sorting device. Target users are contract logistics services with short-term contracts of some 2 to 5 years or companies with cyclical variation in business. In addition, the Hub2Move allows the simple expansion of logistics service at remote sites in global supply chains.

Despite the anticipated benefits resistance exists against the application of the concepts of autonomous decentralized control and Hub2Move. This refers to both the suppliers and the user of those systems. The biggest return of the suppliers is now in the delivery and the adaptation of customized software. Secondly, they make profits with the system know-how as they are responsible for the overall functionality of a system. This risk of total responsibility is compensated by the return. Competencies in the design and construction of material handling techniques are only in the third place. Potential users of autonomous decentralized systems and the concept Hub2Move perceive even more risks based on the fact that they have to take much more responsibility for the system functionality. The provision of appropriate data and the anticipatory adjustment of properties of such a flexible system make it necessary to change organization, monitoring and management of those systems. For the effective application of these innovative approaches it is necessary to provide enhanced planning methods and tools invalidate the retention. Especially for the party of manufacturers it is one of them that they offer advanced operational concepts that enable them, for example, with the outsourcing and leasing of complete material handling systems to new business opportunities.

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