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Rationales for Holonic Manufacturing Control

Stefan Bussmann
DaimlerChrysler AG
Research and Technology
Alt-Moabit 96a, D-10559 Berlin
email: Stefan.Bussmann@
daimlerchrysler.com

Duncan C. McFarlane
Institute for Manufacturing
University of Cambridge
Mill Lane, Cambridge, CB2 1RX, UK
email: dcm@
eng.cam.ac.uk

Abstract. This paper is concerned with providing a clear business basis for the emerging research field of holonic manufacturing systems. The holonic approach is to develop highly flexible manufacturing operations from a set of readily reconfigurable building blocks, which are designed to integrate easily and collaborate dynamically with one another as production demand changes. The business basis is assessed through a requirements deployment process which establishes a link between business trends and requirements on the manufacturing operations and control systems in particular. These control systems requirements are compared to the anticipated control system properties of holonic manufacturing systems.

1 Introduction

The field of Holonic Manufacturing was initiated in the early 1990's [1, 2] to address the upcoming challenges of the 21st century. It is intended to provide a building-block or "plug and play" capability for developing and operating a manufacturing system. Since 1990, an increasing amount of research has been conducted in holonic manufacturing over a diverse range of industries and applications. (For a representative cross-industrial sample see [3-13] and numerous references therein). Yet the slow and limited industrial take-up indicates that it is still difficult to convince potential users of the benefits of this approach. This paper will attempt to address this difficulty, which is partly due to the perceived mismatch between contributions from holonic manufacturing systems and the business benefits they should deliver.

To resolve this issue, this paper will provide a detailed analysis of the requirements that current business trends will place on manufacturing operations, and in turn, will assess the type of control system required to achieve these requirements. The focus on control systems reflects the particular area that most holonic manufacturing developments have addressed to date. The paper will also present a vision for holonic manufacturing systems and detail the contribution of control systems in this context. Finally, we will compare the control system properties proposed within holonic manufacturing systems with those required to support current business trends.

2 Manufacturing Requirement Analysis

Manufacturing operations are not an end in themselves, but serve as a means to achieve the business goals of a company. It is therefore essential for an evaluation or comparison of manufacturing concepts to identify the requirements on the manufacturing process against which the concepts should be evaluated. These requirements are derived from the business goals and the given or expected market conditions. Business goals and market conditions, however, may change over time and thus the set of manufacturing requirements. A manufacturing approach that has been sufficient until now, may result in a poor performance in the future. Consequently, manufacturing concepts should not only be evaluated against the existing requirements, but also against future (possibly unknown) requirements.

This section therefore looks at the current business trends and shows how these will change the manufacturing environment. The new manufacturing requirements are then used to derive requirements on the control of future manufacturing systems. This process is outlined in Figure 1. (Note that there are other contributors to the manufacturing requirements that we will not deal with in this paper.) The manufacturing and control requirements identified will serve as the criteria for evaluating the manufacturing concepts in later sections.

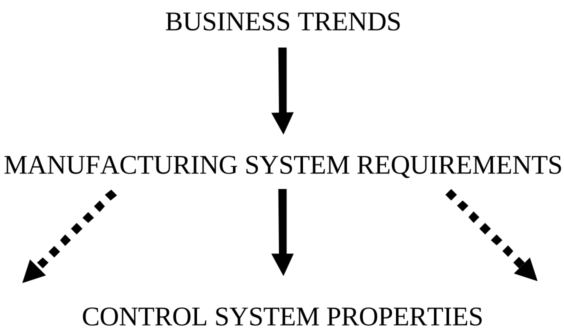

Figure 1: Requirements Break Down Process.

2.1 Business trends

It is difficult to estimate what the business requirements of the 21st century will be. The current requirements of producing goods of a specific quality at low costs will certainly remain in place. But the current market trends suggest that additional requirements will arise which will determine the competitiveness of a company and thus its survival in the next century.

Recently, the manufacturing industry has been facing a continuous change from a supplier's to a customer's market. The growing surplus of industrial capacity provides the customer with a greater choice, and increases the competition between suppliers. Aware of this power, the customer becomes more demanding and less loyal to a particular product brand. He demands constant product innovation, low-cost customisation, better service, and chooses the product which meets his requirements best. In combination with globalisation, these trends will even increase in the future.

The consequences for the manufacturing industry are manifold. Companies must shorten product-life cycles, reduce time-to-market, increase product variety, instantly satisfy demand, while maintaining quality and reducing investment costs. These consequences imply

- more complex products (because of more features and more variants),
- faster changing products (because of reduced product life-cycles),
- faster introduction of products (because of reduced time-to-market),
- a volatile output (in total volume and variant mix), and
- reduced investment (per product).

The effects can be summarised as *increasing complexity* and *continual change* under *decreasing costs*.

2.2 New manufacturing conditions

Most existing requirements placed on a manufacturing operation will still apply in the future. These include guaranteed performance, high reliability of equipment, quality assurance, cost minimisation etc. Given the trends described in the previous section, though, additional requirements will become relevant, if not predominant.

2.2.1 Increasing Complexity

A major requirement will be to minimise the complexity of the manufacturing process (despite the likely increases in the variety of products and product ranges). This can be achieved basically by reducing the number of manufacturing system components and by standardising structure of these components and their interaction. Nevertheless, there is a limit to reduction and standardisation, as a complex product requires a certain set of complex operations.

The remaining process complexity must be mastered. This can be achieved on the one hand by creating an intuitive, self-explaining structure of the manufacturing (and control) system, and on the other hand by assuring a well-defined behaviour upon certain actions and events. Ideally, the control layer of a manufacturing system should be completely transparent to the end-user, and any actions or events should exhibit well-known effects on the overall system performance. In particular, the control layer should not introduce additional complexity and the overall behaviour of a manufacturing system should be well-defined under all circumstances.

2.2.2 Constant Product Changes

Constant product changes require the re-use of existing manufacturing equipment. Buying new equipment is either too costly or takes too much time. Re-use of equipment implies the re-use of the units and the re-organisation of the manufacturing process.

Re-use of manufacturing units can be achieved either through flexibility of function or through reconfigurability. A unit is immediately re-usable if the new operations required are part of the range and mix of operations of this unit. High functional flexibility thus increases the chances of equipment re-use. Units equipped (up front) with a large range of operations, however, can be very costly. In contrast, the costs of a unit are often reduced considerably if the re-use is provided through manual reconfigurability. For monthly product changes, this is acceptable. Weekly or daily product changes, though, are likely to require instant unit flexibility.

An analogous requirement applies to process re-organisation. The manufacturing process must be either flexible or reconfigurable in order to deal with the product changes. In the former case, the manufacturing system is sufficiently flexible to change to the new processing steps. In the latter, the manufacturing system itself has to be re-organised in order to create the desired processing steps (including rearrangement of units and re-routing of parts).

2.2.3 Volatile Output

The volatility of the demand forces the vendors to adapt their output to the market. A product sells only when the market demands it. If a company does not supply the right product at the right time, another company makes the deal.

As a consequence, the manufacturing system must be able to vary its production output. This implies scalability of the manufacturing system if the total volume changes, and inter-product flexibility if the product mix changes. Scalability can be achieved either by extending the working time or by adding more resources. Extending the working time is certainly limited to 24 hours a day and seven days a week. The ultimate measure to scale up the manufacturing operations is therefore to add resources.

Inter-product flexibility requires a re-assignment of resources which is similar to the re-use of equipment (cf. section 2.2.2). Only in this case, the resources are re-used for existing, but better selling products.

2.2.4 Reduced Investment and Robustness

The task of managing change becomes even more difficult if it has to be achieved at decreasing costs. A company might even decide not to provide full flexibility or reconfigurability if the costs are prohibitive. The real challenge is to manage change at low costs.

A low investment approach to change management, however, creates a second difficulty, namely that of disturbances. A behaviour which is achieved under scarce resources is vulnerable to (internal and external) disturbances. Future manufacturing operations will therefore require increasing robustness. Robustness can be achieved either structurally or dynamically. Buffers in terms of material or time slack provide structural robustness. System flexibility allows to adapt the process to failures, for instance by using spare resources or re-routing jobs.

2.3 Control requirements

The requirements on the manufacturing system have also implications for the control of such a system. Many requirements can only be achieved if the control system meets equivalent requirements. Requirements like unit flexibility or reconfigurability are mainly hardware issues, but system responsiveness is certainly impossible without some kind of intelligent control. This subsection therefore looks at the consequences of the new manufacturing requirements for the control, regardless of the actual design and implementation of the control system.

I. The architecture of the control should be decentralised and product-/resource-based.

For even small manufacturing systems, a centralised approach to control is practically impossible. A single controller would be too complex, would become a bottleneck, and would be too difficult to change. There must be at least some kind of decentralisation.

Decentralisation, however, can take many forms. For instance, a system can be functionally or geographically distributed. But in order to allow for maximum flexibility, the decentralisation should be product- and resource-based. In a resource-based architecture, every resource contains all control capabilities necessary to process jobs. In particular, a set of resources is able to allocate jobs to resources without a centralised support. The advantage of the resource-oriented approach is that the system can be changed and scaled up fairly easily. Furthermore, the control corresponds in its structure to the manufacturing system and thus reduces the complexity added by the control system to a minimum. The control activities might even become transparent to the end-user. A similar argument applies to equipping orders and work pieces with the necessary control capabilities to get produced.

II. Control interactions should be abstract, generalised and flexible.

A resource-based control system is certainly easier to change and scale up than a centralised or functionally decentralised system. Maximum changeability, however, is only achieved if dependencies between resources are reduced to a minimum. If one resource is changed, but other resources heavily rely on exactly this resource and its specific behaviour, then the change of the single resource entails a lot of changes at other resources (which might in turn entail changes at even more resources).

Consequently, in order to achieve maximum changeability, resources should be de-coupled in three steps:

1. abstract interaction – make no assumption about the internals of other components
2. generalised interaction – make as few assumptions as possible about the other components' behaviour
3. flexible acquaintances and interaction – dynamically decide with whom and how to interact

III. The control should be reactive and pro-active.

In order to respond to short-term changes and disturbances, the control must be reactive. This includes the ability to recognise critical situations, make decisions about the reaction, and perform corresponding actions. In contrast to traditional planning and control approaches, the product- and resource-based architecture also distributes the planning capabilities since they depend strongly on the characteristics of the resources and the product. A resource for instance must also participate in the allocation of jobs or the sequencing of operations. As a result, the control must be reactive and pro-active at the same time.

IV. The control should be self-organising.

The need to adapt the manufacturing process in the face of changes or disturbances will not only affect the resources, but also the organisation of the manufacturing process as a whole. Obviously, in a highly responsive manufacturing system, the organisation must be responsive too and this responsiveness should emerge from any (re-) configuration of the resources and rearrangement of the process.

	standardisation	minimal system structure	intuitive/transp. structure	well-def./transp. behaviour	flexibility	reconfigurability	scalability	robustness
complexity	*	*	*	*				
responsiveness					*	*	*	*
decentralised architecture			*			*	*	*
product/resource based architecture		*	*			*	*	*
abstract/generalised interactions	*			*	*	*		
flexible acquaintances / interactions				*	*	*	*	*
reactive capabilities				*	*			*
pro-active capabilities				*	*	*	*	
self-organisation		*	*			*	*	

Figure 2: Requirements on Manufacturing and Control.

2.4 Summary

The diagram in Figure 2 summarises the mapping between business requirements, new manufacturing condition requirements and control systems requirements as discussed in this section of the paper. Although its beyond the scope of this paper, such a deployment could be generated also for equipment/physical process requirements and human requirements.

3 Holonic Manufacturing Control

As indicated in the previous sections, there is a growing perception that a successful manufacturing business is one which is able to respond rapidly to changes. In order to support this need at the production level, a number of new strategies have been developing since the early 1990's which provide for a more modular, flexibly integrated manufacturing production environment in terms of machines, human operations or computer control systems (see [14] for a number of examples).

Holonic manufacturing is one such new approach which was first proposed in [1,2] and which has received a lot of attention in academia and industry. In particular, the field of holonic manufacturing was selected as one of the six test cases in the Intelligent Manufacturing Systems (IMS) feasibility study program [15] that was set up in 1992. The holonic manufacturing test case was a one-year feasibility study and consisted of five benchmark test beds that were intended to achieve a better understanding of the requirements of the 21st century manufacturing systems and to develop an approach to build future manufacturing systems based on these requirements [5,11,16]. The success of the benchmark tests led to the endorsement of Holonic Manufacturing as an international IMS project in 1994 [12]. Over 30 academic and industrial partners from the IMS regions Australia, Canada, Europe, Japan, and the United States participate in this international collaboration.

Holonic manufacturing is now a significant research activity with involvement from a wide range of academic and industrial organisations both within and outside the consortium mentioned above. In particular we note that the development scope spans more than just the control aspects of manufacturing operations, but includes also human and machine integration issues, although the area of holonic control has received most intensive attention to date. In this section, we will review the basic elements associated with holonic manufacturing, and provide an illustrative "vision" for how a factory based on holonic systems might operate. Finally, we will compare the proposed elements of holonic manufacturing with the set of requirements developed in Section 2 in order to outline where and how holonic manufacturing systems are able to address the needs of 21st century manufacturing operations.

3.1 Concepts

The holonic concept was proposed by the philosopher Arthur Koestler in order to explain the evolution of biological and social systems [17]. He made two key observations:

(i) These systems evolve and grow to satisfy increasingly complex and changing needs by creating stable "intermediate" forms which are self-reliant and more capable than the initial systems.

(ii) In living and organisational systems it is generally difficult to distinguish between 'wholes' and 'parts': almost every distinguishable element is simultaneously a whole (an essentially autonomous body) and a part (an integrated section of a larger, more capable body).

These observations led Koestler to propose the word "holon" which is a combination of the Greek word 'holos' meaning whole and the Greek suffix 'on' meaning particle or part as in proton or neutron. Suda's observation [1] was that such properties would be highly desirable in a manufacturing operation which was subject to increasingly stringent demands and faster changes. He therefore proposed a building block or "holon" based model for designing and operating elements comprising manufacturing processes. Some key properties of a (holonic) manufacturing system developed from this model are (based on [5]):

- Autonomy – the capability of a manufacturing unit to create and control the execution of its own plans and/or strategies (and to maintain its own functions).
- Co-operation – the process whereby a set of manufacturing units develop mutually acceptable plans and execute them.
- Self-Organisation – the ability of manufacturing units to collect and arrange themselves in order to achieve a production goal.
- Reconfigurability – the ability of a function of a manufacturing unit to be simply altered in a timely and cost effective manner.

In this context, a holon is "an autonomous and co-operative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects" [5]. It consists of a control part and an optional physical processing part. A holon can itself consist of other holons which provide the necessary processing, information, and human interfaces to the outside world. A "system of holons which can co-operate to achieve a goal or objective" is then called a holarchy. Holarchies are created and dissolved dynamically.

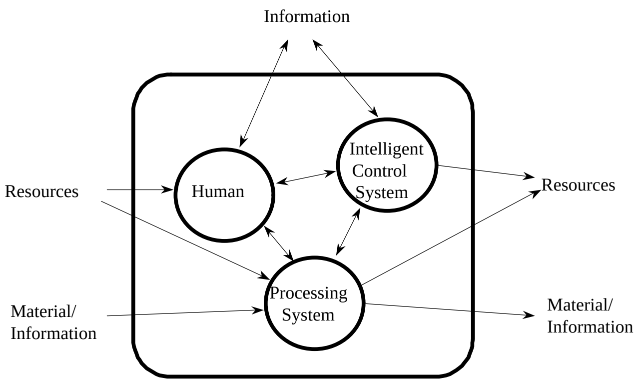

Figure 3: Generic Activity Model for a Holon [5].

3.2 A Vision for Holonic Manufacturing

To illustrate the concept of holonic manufacturing, we present a vision of how holonic manufacturing systems might operate. This vision is deliberately taken to the extreme in order to highlight the key elements of holonic manufacturing.

In the beginning, a holonic manufacturing system only consists of a set of unorganised resource holons which form a manufacturing holon. Upon arrival of an order, however, the manufacturing holon creates an order holon which starts to negotiate with resource holons on the provision of certain manufacturing operations. During the negotiation process, the order holon demands specific properties of the operation, such as high quality or high throughput, while the resource holons try to maximise their utilisation. At the end of the negotiation, the resource holons move to form the agreed manufacturing line and the order holon initiates the creation of work piece holons.

The work piece holons enter the manufacturing holarchy (e.g., from the stock) and immediately bargain for resources in order to get processed. Each work piece holon does so individually and focuses on the next operation(s). Once these operations have been performed at a resource, the work piece re-initiates the bargaining with the remaining (next) operations. The overall organisation of the resource holarchy – initially or subsequently negotiated between order and resource holons – assures that the work piece load is efficiently distributed over the available resources in order to achieve the global goals of this holarchy.

In case of a disturbance, the affected resource holon removes itself from the resource holarchy and goes to a repair booth. The remaining resource holons re-organise themselves in order to account for the capacity loss. From the point of view of the work piece holons, the processing continues as usually, only with less resource holons to bargain with. After repair, the resource holon tries to join the resource holarchy again.

At the end of the order processing, the order holon is removed and the resource holarchy dissolves into the resource holons which then try to participate in new order holarchies.

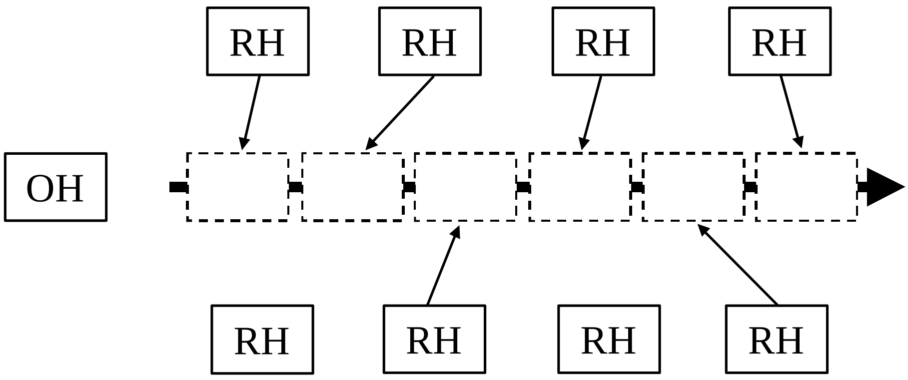

Figure 4: Self-Organisation of Order Processing.

3.3 Addressing Manufacturing Requirements

The short description of the holonic vision of manufacturing has shown that the holonic approach addresses most of the requirements identified in section 2. The requirements are met because of the basic concepts that underpin the holonic approach:

- Holonic Structure – The holonic approach inherently proposes a decentralised, product- and resource-based architecture for the manufacturing operations.
- Autonomy – Each holon has local recognition, decision making, planning, and action taking capabilities, enabling it to behave reactively and pro-actively in a dynamic environment.
- Co-operation – Co-ordination, negotiation, bargaining, and other co-operation techniques allow holons to flexibly interact with other holons in an abstract form. Because of the dynamic nature of the holarchies, each holon must employ generalised interaction patterns and manage dynamic acquaintances.
- Self-Organisation – Holonic manufacturing systems immediately re-negotiate the organisation of the manufacturing operations whenever the environmental conditions change.
- Reconfigurability – Because of the modular approach, holons can be reconfigured locally once the inherent flexibility of the holons has reached its limit.

Control Requirements	Holonic Manufacturing
decentralised architecture	yes
product-/resource-based architecture	yes
abstract / generalised interactions	partly
flexible acquaintances / interactions	partly
reactive capabilities	yes
pro-active capabilities	yes
self-organisation	yes

Figure 5: Comparison of Business Requirements and Holonic Features.

All in all, holonic manufacturing control clearly supports the capabilities required to meet the future challenges. Abstract and flexible interactions are also part of the vision, but generalised interactions and flexible acquaintances are not explicitly mentioned, even though they can be incorporated quite easily into the vision.

4 Conclusion

This paper has identified the business requirements of the 21st century and has derived requirements for the manufacturing operations and their control. It has also presented the concept and vision of holonic manufacturing and has shown that this approach meets the upcoming manufacturing and control requirements. As a result of this comparison, it can be concluded that holonic manufacturing is an approach that will enable a company to meet the manufacturing challenges of the next century.

The comparison, however, has also identified a small gap between the business requirements and the holonic vision. It will be left to future research to extend and detail the holonic vision in order to cover all the requirements. It will also be a future task to show when implementing holonic systems in the factory that this approach can also meet the traditional requirements like guaranteed performance, quality assurance, maintainability, or operability, which have not been discussed in this paper, but which still apply.

An open question remains as to how far the current holonic research addresses the holonic vision, and thus the real business requirements. In other words, to what extent there is a gap between the holonic vision and the techniques currently available to realise this vision. This discussion will be topic of an upcoming paper [19].

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