Developments in Holonic Production Planning and Control

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Abstract

The field of Holonic Manufacturing was initiated in the early 1990's to address the upcoming challenges for manufacturing operations in the 21st century. It is intended to support for highly responsive organisations by providing a modular building-block or "plug and play" capability for developing and operating a manufacturing production system in order to support a more responsive organisation. The holonic approach can be viewed as an alternative to more hierarchical operations management methods such as those based on Computer Integrated Manufacturing (CIM). Since 1990, an increasing amount of research has been conducted in holonic manufacturing over a diverse range of industries and applications, with a strong emphasis on how holonic systems will perform the different planning and control functions required to manage a production operation. The planning and control work to date has, however, been focussed on specific problem formulations and solution strategies. The intention of this paper is to provide an overview of the use of holonic manufacturing concepts in production planning and control which is accessible to both practitioners and researchers in the area. The aims of the paper are:

- To clearly define what is meant by a holonic manufacturing system and to demonstrate the relevance of its development to production planning and control.
- To motivate holonic manufacturing based on a business rationale, demonstrating specifically how it can support improved responsiveness and the management of production complexity.
- To review existing work in holonic manufacturing systems relevant to production planning and control and provide an analysis of the scope and applicability of these results.

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. This paper introduces the current state of holonic manufacturing research developments and in particular assesses the contributions being made to the field of production planning and control.

1.1 Holonic Manufacturing Systems

We begin by providing some simple descriptions and definitions of *holons* and *holonic manufacturing systems*. We define a holon as "an autonomous and co-operative building block of a manufacturing

publ. in *Int. Journal of Production Planning and Control*, Vol. 11, No. 6, 2000, pp. 522 —536.

system for transforming, transporting, storing physical and information objects" [3]. It consists of a control part and an optional physical processing part. (See Figure 1.) Hence, for example, a suitable combination of an machine tool, an NC controller, and an operator interacting via a suitable interface could form a holon which transforms physical objects in a manufacturing environment. Other examples of manufacturing holons could be products and their associated production recipes, customer orders and information processing functions.   A holon can itself also 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 [3]. Holarchies can be created and dissolved dynamically depending on the current needs of the manufacturing process.

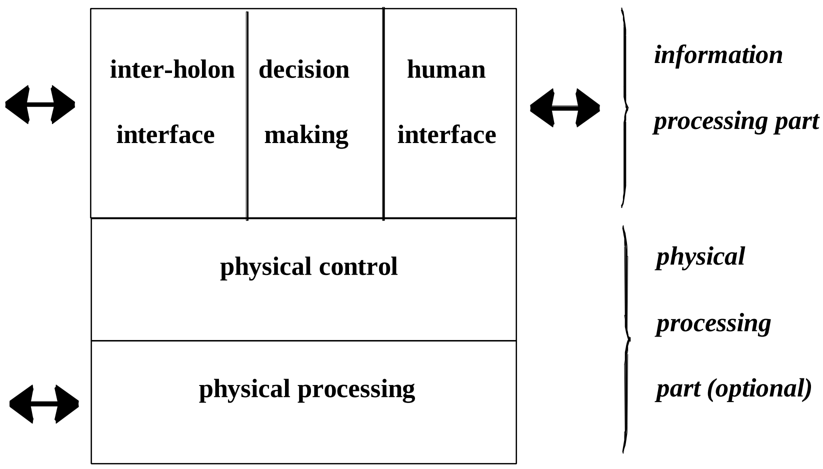


Figure 1   General architecture of a holon [4]

Hence, the intention is that a combination of different holons is responsible for the entire production operations, including not only the production planning and control functions, but also the physical transformation of raw materials into products, the management of the equipment performing the production tasks and necessary reporting functions. In this case the set of holons is referred to as a holonic manufacturing system. A holonic systems view of the manufacturing operation is one of creating a working manufacturing environment from the bottom up. By providing the facilities within holons to both (a) support all production and control functions required to complete production tasks and (b) manage the underlying equipment and systems, a complete production systems is built up like a jigsaw!

Since 1990 there has been a significant amount of reported research and a wide range of publication produced that refer to control systems in a holonic context. These have ranged from conceptual descriptions of holonic systems [1-3, 5-13], to specific architectures [3, 4, 14-23], to operating methodologies [22, 24-41] and simulated or prototype implementations [22, 31, 35, 42-51]. While this work has been documented faithfully, it has been in general difficult a) to arrange the different research activities into a single organised picture and b) to position this work in the context of existing work in related fields.

1.2 Production planning and control in a Holonic Manufacturing Context

One of the key motivations for this review has been the opportunity to examine the role of holonic manufacturing within the broader context of production planning and control methods. It is important to note however that holonic manufacturing systems and production planning and control systems are in some ways, not directly comparable concepts. Holonic manufacturing is an approach to defining and specifying manufacturing production systems (in this sense it has strong links to Computer Integrated Manufacturing or CIM), while production planning and control represents a suite of solutions to different decision making problems arising in production. The overlap between holonic manufacturing systems and production planning and control systems is that, as part of their operations, holonic manufacturing systems must support the same basic functions as conventional production planning and control systems as well as addressing additional tasks required to ensure a fully functional manufacturing operation. Because of the bottom-up approach discussed in the previous section, holonic manufacturing systems support a class of production planning and control methods which are physically distributed and involve local decision making. The relationship between holonic manufacturing systems and production planning and control systems is illustrated in Figure 2.

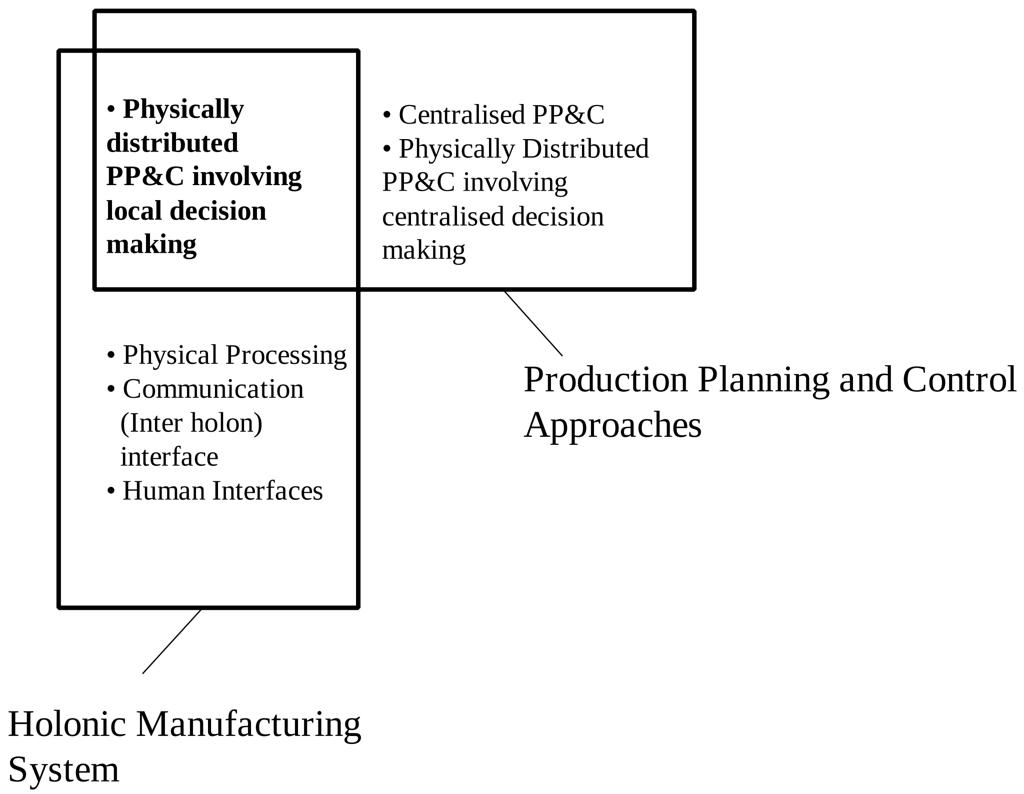


Figure 2 Relationship between Holonic Manufacturing and Production Planning and Control (PP&C)

Another further point which is important for this review is that the holonic systems approach is primarily an *integrating* methodology for the development of *distributed* manufacturing operations which support local decision making – in much the same way that CIM has been for a hierarchical, centralised operations in the past. (See [52] for a detailed comparison between CIM and holonic manufacturing.) Hence, like CIM, holonic manufacturing approaches have already exploited and will continue to exploit many existing technologies and methods. In particular, in the context of production planning and control, many of the holonic approaches we will discuss in Section 3 have their origins in existing distributed problem solving methods. For example, the execution and scheduling approaches emerging from the holonic literature have many characteristics in common with existing developments in *heterarchical manufacturing control* (see, for example, [53-57]), *intelligent scheduling* (see [58], [59] and the references therein) and methods of *distributed artificial intelligence* (see, for example, [60-65]). In [4] the particularly important role of *agent based* methods in a holonic manufacturing environment is examined.

1.3 Structure of the paper

The paper is structured as follows. Because this paper is intended to be a reference for both academic and industrial practitioners, in Section 2 we will outline some of the industrial conditions that have driven the development of methodologies like holonic manufacturing, and provide a simple, informal illustration of the way in which a factory driven on holonic principles might operate. In Section 3 we then provide a systematic review of the contributions in the holonic manufacturing literature to production planning and control. Section 4 will provide conclusions and summarise outstanding requirements for holonic production planning and control.

2. RATIONALE AND APPROACH TO HOLONIC MANUFACTURING

The intention of this section is twofold. Firstly, we will examine current and future manufacturing business drivers in order to broadly outline requirements for future production planning and control. Secondly, we will outline a vision for a holonic factory and will illustrate a number of the different production planning and control features required to support this factory. We will then discuss to what extent these features match those requirements generated from the business driver analysis.

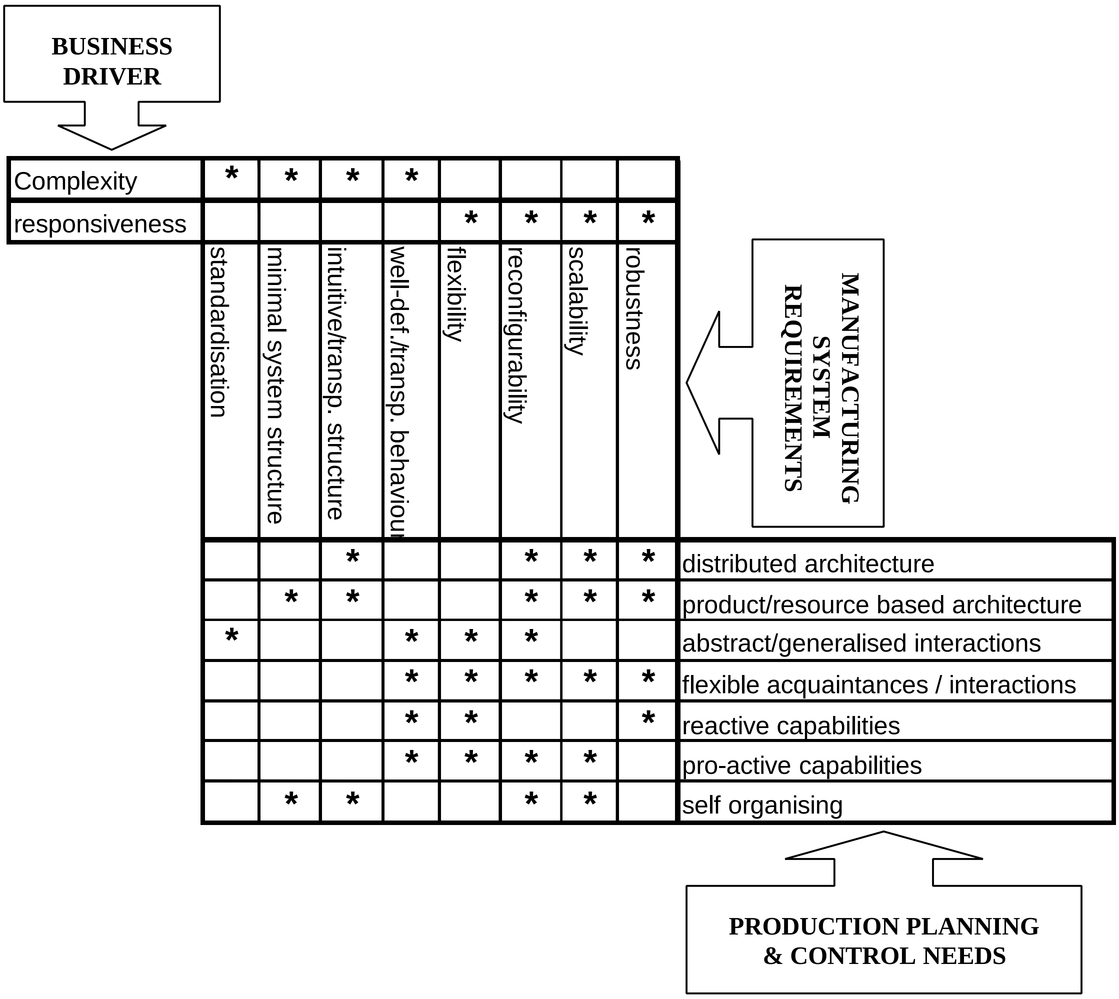
2.1 Requirements Analysis for Holonic Control

Manufacturing industry is currently 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 has become 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 of these trends 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 of these trends can be summarised as *increasing complexity* and the need to *respond to continual change* under *decreasing costs*. To meet these new business challenges, manufacturing operations require additional functionality, like robustness, scalability or reconfigurability, while maintaining simple and transparent processes. Figure 3 summarises the linkage between the general business trends and the manufacturing requirements, where the link is indicated by an asterisk '*' .



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

Figure 3 Additional Production Planning and Control Needs [66]

Figure 3 also illustrates a linkage between the necessary manufacturing requirements and the specific needs this places on production planning and control. In [66], it is argued that conventional production planning and control approaches can no longer support a manufacturing operation attempting to meet these increasingly difficult demands. Regardless of the way in which different production planning and control functions are designed and implemented, these new business drivers imply a distributed, flexible and self-organising production planning and control approach. [66] also provides more details of each of these needs, which are merely summarised here:

I. *The architecture of the control should be distributed and physically-based*, in that elements of the different production planning and control actions (planning, scheduling, execution, machine control, device control) align with physical objects such as products and production resources.

II. *Control interactions should be abstract, generalised and flexible.* Maximum reconfigurability of distributed control operations is only achieved if dependencies between the different components providing the (distributed) control are reduced to a minimum. Hence, rather than involving predetermined, static connections between elements, in order to achieve maximum reconfigurability, interactions between manufacturing components (e.g. resources, products, orders) should be de-coupled in three ways:

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 both reactive and pro-active* in order to respond to both unexpected short-term changes and disturbances, and to be able to anticipate and prepare for critical situations.

IV. *The control should be self-organising* in order to adapt the manufacturing process in the face of changes or disturbances which will not only affect the resources, but also the organisation of the manufacturing process as a whole.

For the purposes of comparison with these requirements, we next develop a description for production planning and control as it might be performed in a holonic manufacturing environment.

2.2 A Vision for Holonic Manufacturing Operations

The holonic concept was proposed by the philosopher Arthur Koestler in order to explain the evolution of biological and social systems [67]. 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, 2] 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 similar in concept to the one outlined in Figure 1. Some key properties of a (holonic) manufacturing system developed from this model are (based on):

- 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.

We will demonstrate, via a simple illustrative example, how a system with these properties might operate and consequently how it is able to address the requirements derived in Figure 3. This illustration is deliberately taken to the extreme in order to highlight the key elements of holonic manufacturing.

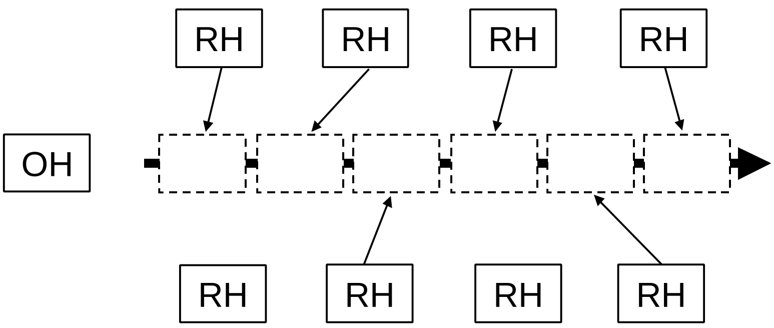


Figure 4 Self-Organisation of Order Processing.

Initially (referring to Figure 4), a holonic manufacturing system consists only of a pool of unorganised *resource* holons. Upon arrival of an order, an *order* holon is created which begins to negotiate with resource holons regarding the provision of certain manufacturing operations. During the negotiation process, the order holon demands specific properties required from the operation, such as high quality or high throughput, while the resource holons try to optimise their utilisation. At the end of the negotiation, the resource holons combine to form the agreed manufacturing line (i.e. a manufacturing holarchy) and the order holon initiates the creation of *product or workpiece* holons.

The product holons enter the manufacturing holarchy (e.g., from raw materials stock) and immediately bargain for resources in order to get processed. Each product holon does so individually and focuses on the next operation(s). Once these operations have been performed at a resource, the product re-initiates the bargaining with holon representing the remaining (next) operations. The overall organisation of the resource holarchy – initially or subsequently negotiated between order and resource holons – assures that the product 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 product holons, the processing continues as usual, only with fewer resource holons to negotiate with. After repair, the resource holon rejoins the resource holon pool 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.

This short description of the holonic vision of manufacturing has indicated that a holonic approach can address many of the requirements (I-IV) identified in section 2.1. The requirements are met because of the basic concepts that underpin the holonic approach:

- Holonic Structure – The holonic approach inherently proposes a distributed, product- and resource-based architecture for the manufacturing operations. (Requirement I)
- 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. (Requirements I,III)
- 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. (Requirement II)
- Self-Organisation – Holonic manufacturing systems immediately re-negotiate the organisation of the manufacturing operations whenever the environmental conditions change. (Requirement IV)
- Reconfigurability – Because of the modular approach, holons can be reconfigured locally once the inherent flexibility of the holons has reached its limit. (Requirements II,IV)

The vision presented here for holonic manufacturing appears promising in the sense that it aims to achieve a number of the outstanding requirements for current and future manufacturing production planning and control. However, this vision is still some way from being realised in practice. Hence, having motivated the necessary features of holonic production planning and control systems we now turn to establishing the current state of the art of holonic manufacturing in this area.

3. DEVELOPMENTS IN HOLONIC PRODUCTION PLANNING AND CONTROL

3.1 Overview

This section intends to review the current contribution of holonic manufacturing to different aspects of production planning and control approaches. Specifically it will classify and summarise reported developments, identify novel contributions and indicate where significant gaps remain to be addressed

The review will be structured around the conventional MESA architecture [68] for production planning and control environments given in Figure 5. This is intended to allow the reader to form more direct comparisons with existing approaches to planning, scheduling, execution, machine and device control. (It is assumed for the purposes of this review that the reader is familiar with conventional approaches to these problems.) We do note however that one of the key roles of holonic manufacturing systems is to provide flexibility and interoperability between the levels in Figure 5 and hence to challenge the universal applicability of such an architecture.

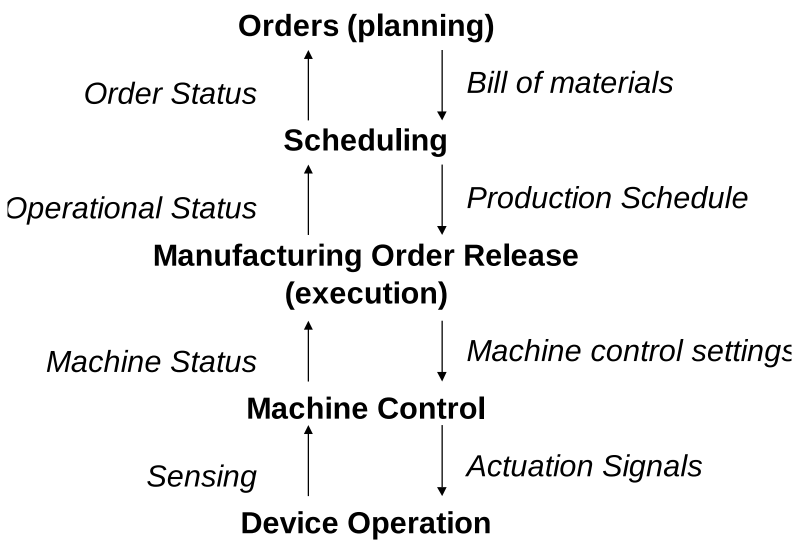


Figure 5 Typical Manufacturing Control Hierarchy

In order to simplify the discussions that follow, we will assume a common description of a manufacturing process operating on holonic principles. In line with the holonic vision in Section 2.2, the process is assumed to comprise some or all of the following elements:

- Resource holon – a single unit comprising one or more physical processes or transportation resources, its control systems and any necessary human based operations.
- Product holon – a unit comprising the physical product being produced and the human and computing support necessary to initiate and monitor its production
- Order holon – a unit representing the requirements of a particular order, including information such as product qualities, due dates, costs, priorities. It may also encompass physical products in either a finished or unfinished state and / or information about order status.
- Co-ordinator holon – an optional support unit (computer or human based or a combination of both) providing a level of co-ordination between the different holons, and ensuring that the global goals of the factory are represented.

Each of these holons – once created – is assumed capable of a degree of local reasoning and decision making and an ability to communicate in an interactive manner with other holons. We will discuss the way in which these capabilities support different production planning and control issues in the next section. For more details on the overall descriptions or architectures of individual holons or their connection infrastructure systems, the reader is referred to [3], [4], [25] and particularly to reports on the so called *Product - Resource - Order - Staff Architecture* (PROSA) proposed in [15]. In this paper we are not examining the way in which holons are designed and built but rather the way in which they interact in order to address production planning and control issues.

3.2 Holonic Production Planning and Control Review

In this section we examine the different approaches being taken by holonic systems developers to holonic planning and control. In general, because of the way holonic systems are structured, holonic planning and control solutions are distributed in terms of decision making and the coherence of local decisions is achieved through *co-operative* interactions (negotiations, for example) between holons. (See Figure 6.) More details of the properties of these type of co-operative systems are given in [69].

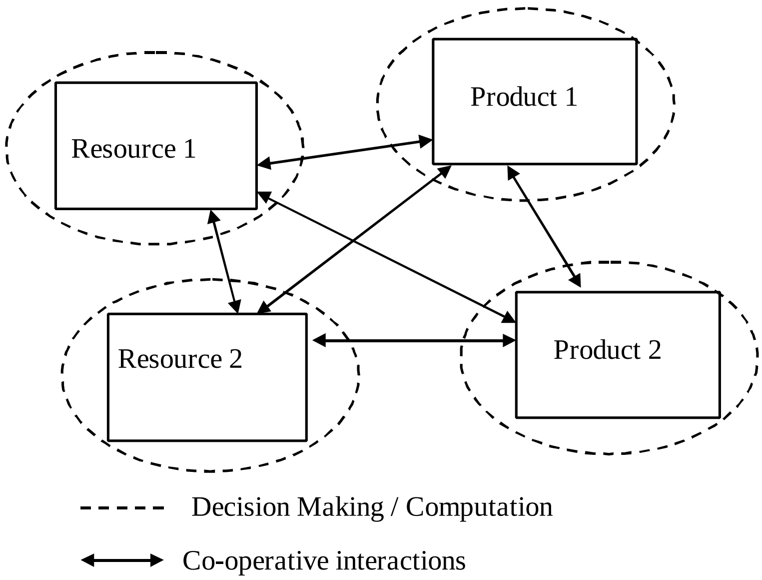


Figure 6 Holonic Control Mechanism

We will describe how the current developments in holonic manufacturing apply to each of the control activities in Figure 5, (i.e. planning, scheduling, execution, machine and device control) and for each of these items we will describe

- the standard problem addressed and the shortcomings of some of today's solutions
- holonic approaches being developed to address this problem, their level of their development and to what extent they can address these shortcomings
- the novel features of the holonic approaches to the problem

Because few authors have reported comparative data, it is, in general, not possible to provide a critical evaluation of the performance of holonic control solutions compared to more conventional approaches. Hence comments on performance are limited to qualitative assessments of the solutions.

3.2.1 Planning

Commercial planning solutions such as MRP and MRPII today cover a wide range of planning tasks (as well as scheduling tasks) in addition to the central production planning functions. We restrict the following discussions on planning to two basic steps:

1. *The decomposition of an order into a sequence of production operations.*
2. *The nominal allocation of operations to resource types (but not specific resources or times)*

For the purposes of this review the assignment of operations to specific resources and determination of timing is a scheduling rather than a planning function.

Holonic planning of production operations has been addressed by a number of workers (see in particular, [44] , [21], [38, 39], [35], [70], where planning at the factory level is addressed and [46] , [45] which examines a limited planning of a individual robot cell). Because of the autonomous and distributed nature of the holonic elements, the associated holonic planning methodologies typically involve a mix of local decision making and co-ordination between individual units. Approaches to holonic planning described in the literature typically involve a number of the following steps:

1. Each product holon performs a decomposition of the supplied product specification into constituent parts or sub assemblies.
2. For each product the manufacturing operations needed are identified (by the product holon).
3. The type of resources to provide operations needed are selected via interaction approach between product and resource holons
4. An interactive process involving resource holons and product holons for determining a suitable set of operations.
5. A full make sequence (assembly plan) is finalised and this normally resides with the product holon

We note that this assumes – *a priori* – that the products required to fulfil an order have already been identified. Clearly, a number of these steps are common to any planning method. However, there are several features specific to a holonic approach to planning:

- The processes of operation identification and selection, and sequence determination are distributed and involve interactions between the product (part) holon and resource holons (see, for example, [71], where the planning process is managed by contract bidding mechanism). In [44], [21] additional *operation* holons representing a decomposition of the production steps needed are generated as an intermediate software elements to assist the interactive planning process.
- There is a distributed and interactive decomposition of an order into individual manufacturing tasks. In [13], for example, a manufacturing cell holon, representing a cluster of machine or resource holons, manages the decomposition of a production request by interactively consulting the product holon and referring where necessary to other resource holons.
- When planning is complete, sequence information is allocated to the product holon, which it then uses in scheduling and execution phases.

The benefits of a holonic approach compared to more conventional approaches are principally due to the distributed and interactive nature of the planning process, enabling new products and / or production resources to be introduced simply without major system alterations. The close connection between the individual holons and the physical resources they represent also enables planning to maintain a close alignment with the (dynamically changing) capabilities available on the shop floor.

A more complete vision for holonic planning compared to those reported to date might involve an order holon intelligently deducing which operations are required to complete the order and comparing this with the set of available resources in order to determine whether adequate facilities are available to complete the order in time.

A further general observation based on the holonic manufacturing literature as a whole is that most holonic solutions described assume that a planning phase has *already* occurred. That is, a set of candidate resources have been identified, and a set of operations to complete an order have also been determined, and hence – referring to Figure 5 – the first production control problem to address is scheduling.

3.2.2 Scheduling

Holonic scheduling represents a significant proportion of the all the work undertaken in the holonic production planning and control area and has been considered, for example, in the context of flexible manufacturing systems [29], [44], [22], assembly lines [48], job shop [31], assembly and machining cells [46],[45], [5], continuous process lines [42],[13], and plant wide maintenance [41]. Additionally, generic scheduling methods have been presented in [72], [73], [35]. One reason for this level of activity has been the level of development of intelligent scheduling techniques (see, for example, [58], [59] and the references therein) and distributed factory control algorithms (see, for example, [55], [56], [74] and the references in [62]) both of which are generally compatible with an approach to holonic scheduling (and also execution to a less extent. Both approaches attempt to provide for more dynamic resource and time allocation capabilities than can be achieved via conventional off-line scheduling methods.

In this discussion we assume that scheduling (in a discrete manufacturing environment) simply involves

1. *The allocation of production operations to specific resources*
2. *The specification of the timing (start, duration, completion) for those operations*

In particular, we distinguish scheduling from the shop-floor control issues which are associated with the execution of the schedule within a cell or production line. (In a holonic systems context, this boundary is often blurred.) Following the description of a holonic systems in 3.1, a holonic scheduling approach is exemplified by an interactive selection process between product and resource holons whereby either

a) Product holons seek assistance from resources in order to be made in accordance with any constraints imposed by the order such as due date or production cost or,
b) Resource holons seek tasks from product holons which enable them to achieve particular utilisation or cost targets or,
c) A combination of a) and b) is followed.

There is often however a need for centralised co-ordination to ensure that the localised interchanges between individual product and resource holons are compatible with the overall goals or targets of the factory.

The key characteristics which typify a holonic scheduling approach are:

1. A local decision making and computational capability associated with each holon.
2. A co-operative interaction strategy which governs the way in which holons exchange information and determine mutually acceptable solutions.

3. An interchange mechanism or protocol which manages the exchange of the message types needed to execute the co-operative strategy.
4. A means of ensuring that the global concerns of the factory are addressed
5. A degree of central co-ordination (not present in all solutions)

Hence, as for the planning case, a holonic scheduling approach differs from a conventional scheduling approach primarily in terms of the distribution of the computation and decision making functions and the interactive (and largely co-operative) nature of the communications between the holons. The benefits that can be expected from these approaches mirror the benefits cited in the intelligent scheduling literature [58, 59]. The ability to a achieve a closer and more intuitive link to activities on the shop floor means that the scheduler should be more robust to unexpected production disturbances, and more readily ammenable to (controlled) local user interventions.

Referring to the key characteristics above, some of the key themes to emerge from the work on holonic scheduling to date are as follows:

- **Central vs Distributed Problem Formation-** the distributed AI literature (see for example [65] and the reference therein) differentiates between two classes of distributed computation problems: *distributed problem solving* and *multi agent systems*. In both cases a computation is performed by distributed nodes which interact in a coordinated manner. In distributed problem solving the problem to be solved is formulated centrally, and then distributed to local computational nodes. In multi-agent systems the problem both originates and is resolved at the local nodes and the resulting overall solution is *emergent.* The approaches to holonic scheduling reported to date are more aligned to distributed problem solving approaches (see for example [22, 44], [42]). The challenge of achieving global performance imposes a significant hurdle to multi-agent systems approaches.

- **Local decision making / computational techniques** local decision making approaches reported to date are typically driven by the computation of a local cost function which is constrained by global production requirements ([44], [42], [31], [29]). The Lagrangian relaxation methods developed by Luh et al [22, 34, 40] represent the most sophisticated of these.

- **Co-operative Interaction Strategy:** Co-operation is typically achieved via bidding or constraint satisfaction mechanisms. These are used to either directly adjust local processing parameters (e.g. start times, production times, production set points), or to revise the local cost function conditions, requiring a revised local computation.

- **Interchange Mechanism** To date the dominant protocol used for managing problem-solving communications is the Contract Net Protocol [71] which provides procedures for:

  - task announcement
  - task announcement processing
  - bidding
  - bid processing
  - contract processing
  - managing negotiation trade-offs

Contrary to popular opinion, Contract Net in its basic form does *not* represent a co-operation strategy in itself - it is merely a framework for supporting task distribution strategies.

- **Degree of Central Co-ordination:** We have previously noted that all elements of a holonic scheduler (as with any other control function) must reside with one or more of the holons involved in the manufacturing operation. Ironically, this does not preclude the possibility of some or all of the scheduling function being centralise. In fact all holonic scheduling approaches report on some form of central co-ordination for ensuring coherence of locally produced decisions. In [75], for example, a centralised scheduling holon is described which is essentially a single software holon interacting with other holons to execute shop floor tasks and to receive updates on execution status. In a less extreme manner, in [22, 41] co-ordinator holons are established to manage the compatibility between different local elements of the schedule. Other approaches dedicate this role (temporarily) to the relevant product holon [35], [5], [42] although the performance of such approaches in industrial strength applications is to be questioned. Hence, in contrast to the heterarchical shop floor control and scheduling approaches reported in [54, 55, 57], the holonic solutions proposed present a compromise between hierarchical and heterarchical methods. (See [37], [52] for further discussions on this issue.)

To conclude, scheduling approaches within holonic systems research are generally underdeveloped, particularly compared with the distributed scheduling solutions developed within the Intelligent Scheduling domain, where fully developed, industrial strength systems have been developed and trialled. The main limitation of holonic scheduling applications to date is that most are centralised to some degree, thereby allowing for only limited autonomous behaviour of local resource or product holons.

3.2.3 Execution / Shop Floor Control

Execution represents that part of manufacturing control where theoretical expectations and physical production realities meet. For the purposes of this discussion, we assume that execution or shop floor control involves:

1. *The initiation of tasks (production, transport etc) involving actual start times and actual production settings*
2. *The control of the execution of the tasks*
3. *The monitoring of task status*
4. *The termination of the tasks*

Execution, as discussed in the context of holonic manufacturing systems, is predominantly concerned with a) ensuring that the holon is capable of establishing and maintaining autonomous operations and b) that it undertakes tasks compatible with production requirements even in the face of disruptions. Execution has been addressed in the holonic literature by [45, 46, 51, 76] where the autonomous behaviour of the (resource) holons in each case is managed by an internal model of the operations either using precedence graphs, finite state machines or petri net methods. Such a model is an essential requirement for the holon's self-management and further it is clearly critical for the detection and diagnosis of errors and faults during operation [30]. A further important issue is the relationship between execution and scheduling. In [51] the concept of a *non-interruptible operation* (NIO) is introduced to represent atomic execution steps which cannot be interrupted once commenced and execution is tied closely to a reactive scheduler which is able to respond in finite time to shop floor disturbances. Similarly in [77], the concept of a *primitive sequence* is introduced for the same reasons.

The novel elements of a holonic approach to execution are that a) execution proceeds via a negotiated set of steps rather than a pre-determined sequence and that b) the resources (machines) executing the manufacturing operation are also responsible for the decisions made about the timing and nature of the execution. A clear benefit that emerges here is that the machine operator becomes more integrated with the production decision making processes as well as manufacturing task execution. The holonic control system would then prevent local decisions being made that are contradictory to overall production requirements.

This critical aspect of manufacturing control has received only a limited coverage to date in the holonic literature, but will become increasingly important as holonic systems developments move closer to implementation. A further issue not yet explored in detail is the possibility of closely tying holonic execution to holonic scheduling. This will be discussed in Section 4.

3.2.4 Machine / Device Control

Machine and device control are potentially two different issues but as there are so few simple devices considered in the holonics literature we will combine the review of these two areas.

Machine control involves the initiation, co-ordination and monitoring of the different machine functions or devices required to support the execution of production tasks by an individual machine (e.g. control of a NC machine or multi axis robot)

Device control involves actuation, sensing and feedback control of the physical operations which support a machine or process unit. (e.g. control of a pump or servo motor)

Several papers have considered requirements for numerically controlled (NC) machines in a holonic context [18, 49, 78, 79], although in general these works treat the NC machine as a stand alone unit whose internal controls are conventional. Only in [18] is the possibility of a machine itself running on holonic principles truly considered. In this research, the possibility of individual devices which constitute a machine (e.g. joints on a robot) combining in a co-operative manner is examined, and subsequent increases in flexibility are identified.

Machine and device level activities to date have focussed on integrating capabilities which support autonomous behaviour. [77] and [25] discuss suitable software architectures for integrating machine control with holonic execution and [49] proposes a device driver based approach for coupling individual machines or devices to PC based holonic shop floor control systems. Finally, we note the criticality of functions other than control for supporting holonic operations at this level, both in terms of information systems (monitoring, diagnosis) and mechanical systems (fixturing, pallets, tool management) systems.

Although developments in both holonic machine and device control have been limited to date, opportunities for greater flexibility and disturbance handling present themselves in the way in which trajectories and control actions could be negotiated to suit the current operational environment rather than following predetermined paths. One would expect such a system to be more adaptable to changing conditions arising, for example, from wear, damaged parts, faulty components or sensors.

3.3 Comments on Holonic Control Methods

We conclude this section by summarising some of the primary differences between holonic control solutions and their conventional counterparts. The table in Figure 7 lists the main differences between conventional and holonic approaches to production control.

	Conventional Control Solution	**Holonic Control Solution**
1	Fixed layered, hierarchical architecture representing the different production control problems	No permanent hierarchy of control problems
2	Command/response mechanism provides the basis for the connection between different production control problems	Interactive interchange / simultaneous solution is possible between different production control problems
3	Predetermined solution format to individual production control problems	Solution format determined by the different holons involved
4	Typically a centralised solver for each individual production control problem	Typically a distributed solver, with co-operative interactions between nodes

5	Solutions time constrained by processing power	Solutions time constrained by communications speed
6	Control systems architecture effectively decoupled from control solutions	Control systems architecture tightly coupled to control solutions

Figure 7 Characteristics of Conventional and Holonic Control Approaches

As has been discussed in the previous sections, holonic systems development is in a state of relative infancy compared to more conventional methods which have been deployed over many years and even in comparison to more recent developments such as the application of artificial intelligence methods to individual planning and scheduling problems [58, 59]. Hence the comparison in Figure 7 is based on an optimistic view of a fully functional holonic manufacturing system of the future.

4. CONCLUSIONS

To conclude this review of the state of the art of holonic manufacturing systems, we will highlight those aspects of holonic control systems which are most in need of attention in current and future research.

4.1 State of the Art of Holonic Control Systems

The state of the art review in Section 3 has demonstrated that only a subset of the vision for holonic manufacturing systems outlined in Section 2 has been addressed. The concepts that were described as underpinning the holonic approach were structure (or architecture), autonomy, co-operation, self-organisation and reconfigurability. Of these, co-operative mechanisms have been explored to a degree within the different production control levels, and requirements for autonomy have been established, particularly with regard to the lower level control functions in Figure 5. Numerous architectures for holonic manufacturing systems have been proposed [3, 15, 73], but a rather prominent weakness in the research to date has been the lack of any discussions about the relative performance of the control mechanisms that they support. In particular, holonic manufacturing systems are frequently cited as performing well in the face of disturbances but there has been little reported evidence of them being shown to do so. Any serious industrial commitment to holonic manufacturing systems I the future will require a demonstrated ability to *improve* performance beyond that of conventional systems. Finally, apart from organisational aspects associated in holonic planning there has been little or no attempt to explicitly address the requirements for self-organisation which underpins the flexible response of a holonic system.

To be fully effective, holonic manufacturing requires a complete re-organisation of production operations, which is a costly undertaking. Therefore, it is very important to show and quantify the benefits. Additionally, in order to reduce the high investment costs, holonic manufacturing developers need to provide migration paths to make this transition smoother.

4.2 Future Developments in Holonic Production Planning and Control

There are at least two critical issues that must be addressed before holonic control solutions can be expected to play any significant part in next generation manufacturing systems:

(i) Migration to Full Holonic Production Planning and Control : The review in Section 3 reflects a research activity that has to date aligned itself with the conventional control systems hierarchy in Figure 5. That is, distributed, co-operative solutions have been sought for each of the individual problems on this hierarchy. Few authors however, have truly attempted to question the relatively static *command-response* connections between these layers. These current developments are illustrated in **Figure 8**(b). It is the authors' opinion that a new more holistic approach is required for the control of manufacturing operations, which seeks to achieve co-operative interaction *across* these layers as well as between elements *within* them. For example, a separate planning and scheduling phase is in fact restrictive, because planning can commit an order to a particular make sequence when in fact more than one may be possible and each option may be more or less desirable depending on the current plant state. Hence combining planning and scheduling may be highly attractive, at least if planning options are not deleted until scheduling is considered. A distributed and interactive approach to *combined* planning and scheduling, or *combined* scheduling and execution or even *combined* execution and control should present a relatively straightforward migration from the current state of development. (Refer to **Figure 8** (c)). From these combined solution approaches, the next migration step is to consider systems which support comprehensive manufacturing holons which may seamlessly integrate all of each of the five control functions into their operations (**Figure 8** (d)).

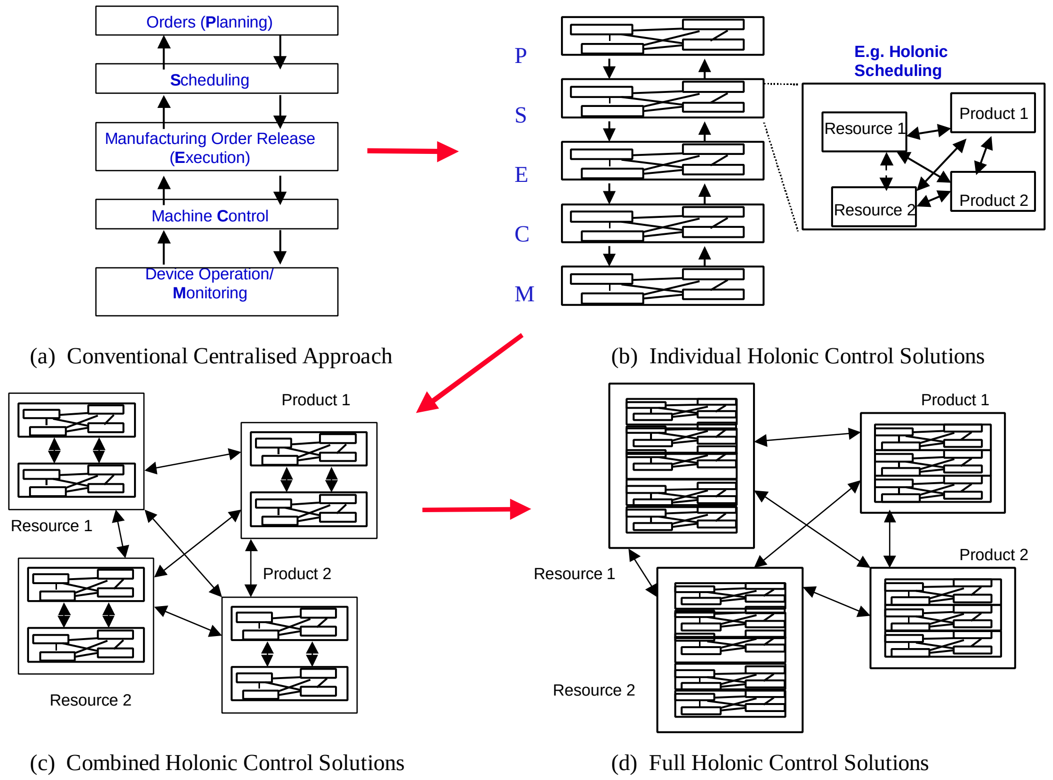


Figure 8 Migration to Holonic Control

(ii) **Establishing Suitable Implementation Approaches with Existingand Future Commercial Computing Systems:** From an implementation perspective, there has been little or no work done in determining the compatibility of the holonic vision with the current or the next generation of industrial control and computing systems. Holonic systems will require a high level of reasoning and computational capability at the shop floor levels, coupled with more flexible communications and more dynamic interfaces to human operators and users. Determining how to construct and interface systems capable of fully supporting holonic operations with existing legacy systems will also be a major issue as holonic systems capabilities reach industrial strength. In the shorter term, suitable migration approaches for the implementation of intermediate holonic control capabilities are required (See, for example, [76], [80].) One such approach involving the combination of PC, Programmable Logic Controller and Machine (robot) controller to provide a holonic control infrastructure for an assembly cell is illustrated in Figure 9.

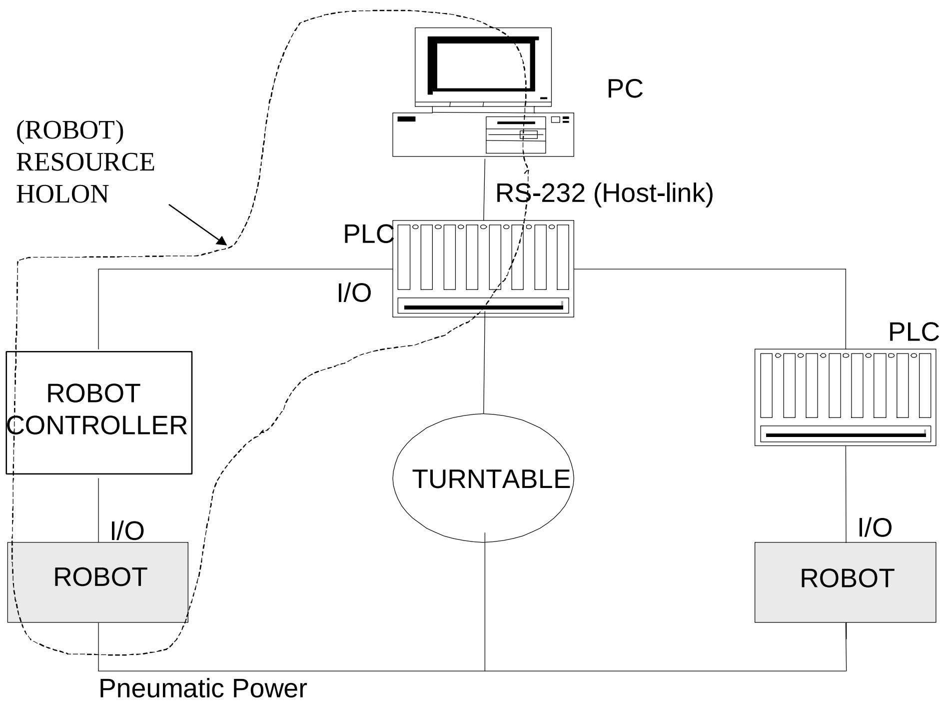


Figure 9 Holonic Control Implemented in Conventional Infrastructure[81]

5. ACKNOWLEDGEMENTS

The authors are grateful for the support of this collaborative work by the ESPRIT Intelligent Manufacturing Systems Working Group. The second author would also like to thank the UK Engineering and Physical Sciences Research Council for their support under the research grant entitled Improving the Responsiveness of Manufacturing Production Systems (1997-99). Finally, the authors would like to thank colleagues Hartwig Baumgärtel at Daimler Chrysler and Jeremy Matson at Cambridge for their help and Dennis Jarvis at CSIRO for providing valuable comments on a draft version of the paper.

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