HOLONIC CONTROL OF AN ENGINE ASSEMBLY PLANT
AN INDUSTRIAL EVALUATION

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Abstract

At the beginning of the 1990s, the *holonic manufacturing* paradigm was proposed (among others) to meet the upcoming challenges in the manufacturing industry. Even though the holonic idea is appealing, its implementation would revolutionize the way manufacturing is done today and thus needs to be thoroughly evaluated before it can be adopted. To this end, an industrial feasibility study for (automotive) engine assembly was conducted within the international holonic manufacturing project. During this feasibility study, the deficits of an existing engine assembly system were analyzed and a new assembly layout and control system was proposed. The new assembly system was then compared to the existing assembly system on the basis of a realistic simulation with plant data. The results of the comparison showed that the holonic approach provides robustness and scalability which is unprecedented in existing assembly systems.

Keywords
Holonic manufacturing systems, manufacturing control, assembly systems, migration, industrial feasibility.

1 Introduction

At the beginning of the 1990s, the *holonic manufacturing* paradigm was proposed (among others) to meet the upcoming challenges in the manufacturing industry [7,8]. Globalization and industrial over-capacity are causing a shift from a vendor's to a customer's market. As a result, companies must shorten product-life cycles, reduce time-to-market, provide mass-customization, and instantly satisfy demand, while maintaining quality and reducing costs. The consequences for the production operations are increasing complexity and continual change wile costs must be reduced [2].

The holonic paradigm advocates the use of autonomous and cooperative manufacturing units, called *holons*, organized in a flexible hierarchy in order to increase the agility and reconfigurability of the manufacturing process. Even though the holonic idea is appealing, its implementation would revolutionize the way manufacturing is done today and thus needs to be thoroughly evaluated before it can be adopted. To this end, an industrial feasibility study for (automotive) engine assembly was conducted in work package seven of the international holonic manufacturing project [10,11].

This paper reports on the results of this feasibility study. In particular, the paper discusses the current deficits of engine assembly (section 2), presents a new assembly layout and control architecture (section 3 and 4), and shows why the holonic approach improves the overall performance of the assembly process (section 5).

2 Case study

The basis for the evaluation of the holonic concepts was the DaimlerChrysler engine assembly plant (NVM) at Stuttgart, Germany, which at that time was the newest engine plant within DaimlerChrysler. The plant produces Mercedes-Benz V6 and V8 engines with a volume of more than 800 units per day.

The assembly process at NVM is divided into the engine block assembly, the cylinder head assembly, the final assembly, the test field, and the shipping area. The assembly process starts in the block assembly when the crankcase is put onto a pallet. The pallet then runs linearly through the different stations of the assembly sections until it reaches the shipping area where it is taken off the pallet and shipped to a car assembly plant, while the pallet is returned to the block assembly.

The assembly stations are either operated manually or automated with the help of robots. Most stations require additional parts to perform the assembly operations. Large parts, such as the crankcase or the crankshaft, are provided at an assembly station by a buffer and an automated

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retrieval system (see figure 1). The transportation of pallets between assembly stations is performed by conveyor belts.

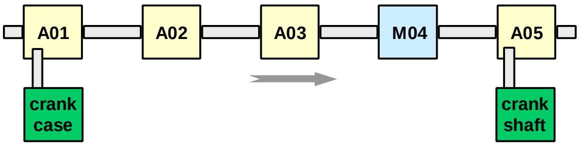

Fig. 1: Beginning of the block assembly.

The assembly system contains nearly no in-process buffers (except for the supply of assembly parts). In case of disturbances, assembly stations can only be de-coupled by buffering pallets on the conveyor belt between two stations. The conveyor belts, however, are typically only a few meters long so that only a few pallets can be buffered. With a cycle time of less than 90 seconds, these buffers last only for a few minutes.

The full NVM assembly process – from the block assembly to the shipping area – was modeled and analyzed in an event-based simulator. The data necessary to parameterize the different simulation components, in particular the probability distribution of machine and logistical disturbances, were taken from the plant reporting system. The resulting simulation model was validated by comparing the predicted behavior, in particular the system throughput, to the actual performance of the plant. On the basis of this simulation model and the discussions with the plant engineers, an extensive analysis of the assembly system was performed in order to identify the main deficits of the existing assembly system.

The analysis revealed that the existing assembly system mainly suffers from two severe deficits. First of all, the linear assembly line is very sensitive to (machine or logistical) disturbances. If a station breaks down or stops because of a supply shortage, soon stations up the line have to stop because workpieces cannot proceed, and stations down the line run out of workpieces. Such a disruption of the assembly process has a severe effect on the production performance and in particular on the stability of the throughput.

Secondly, the existing assembly system cannot be scaled to higher production volume as the demand increases. The plant must either run overtime (which is limited) or purchase a second assembly line. Purchasing a second assembly line, however, doubles the investment costs, even if the demand increases by less than 100%. Consequently, the costs per product increase.

As a result of the analysis, the technical goal of the feasibility study was therefore to increase the robustness and scalability of the assembly system, while maintaining the high volume and the low costs per product. Such a goal, however, is no longer achievable by continuously improving the existing system, but requires a radical change in the organization and the control of the assembly process.

3 Holonic assembly system

The holonic concepts offer a completely new approach to organizing and controlling production processes. A *holonic manufacturing system* (HMS) consists of autonomous, self-reliant manufacturing units, called *holons*. Any unit, like for example a machine, a conveyor belt, a workpiece, or an order can be a holon as long as the unit is able to create and control the execution of its own plans and/or strategies [4]. Holons cooperate with other holons during the production process in order to accomplish the production goals. Cooperation, in form of coordination and negotiation, develops wherever and whenever necessary, usually along the material and information flow.

A system of holons which can cooperate to achieve a goal or objective is called a *holarchy* [4]. Holarchies are recursive in the sense that a holon may itself be an entire holarchy that acts as an autonomous and cooperative unit in the enclosing holarchy. Holons within a holarchy may dynamically create and change communication and cooperation structures. Moreover, holons may engage in multiple cooperation activities at the same time (for a discussion of holonic concepts see also [6, 9]).

The implementation of holonic concepts on the shop floor, however, would be a radical shift from the existing linear (and thus rigid) organization of the production process and its hierarchical control system to a more flexible process also requiring a more sophisticated control. Such a radical shift would not only induce a high technological risk, it would also invalidate any experience of the engineers in operating the plant, resulting in a longer ramp-up time and in an initially lower productivity of the new system. It is therefore essential to provide a migration path from the existing to the holonic assembly system that reduces the technological risk and accelerates ramp-up.

To this end, holonic concepts are introduced into the assembly process in three phases. The starting point of the first phase is the current layout of the assembly system, in which dedicated assembly stations are linearly connected by conveyor belts (cf. figure 1). In the first phase, this classical layout is extended by flexible buffers. These buffers are located along the main assembly line and can be used as additional buffering capacities in case of a disturbance in the main line (cf. figure 2).

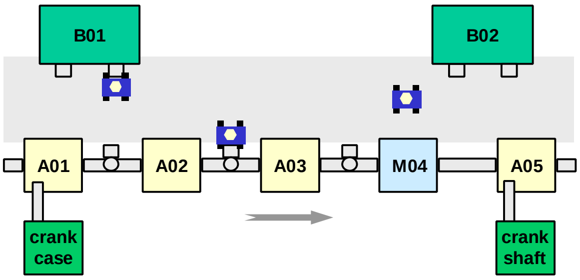

Fig. 2: Introduction of flexible buffers (phase 1).

Let's assume for instance that assembly station A03 suddenly breaks down. Without additional buffering capacities station A02 and soon also A01 have to stop because engines back up in front of the disturbed station, while station M04 and A05 soon run short of supply. Now in the first phase, the engines are taken off the main line in front of a broken station and are transported to a flexible buffer. If a buffer contains engines that have previously been taken off the main line between the broken and the next station, these are transported back to the main line and put on the conveyor belt right after the broken station. Due to this flexible buffering, the main line in front of the disturbance is able to continue processing as long as there is flexible buffering capacity available, and the stations after the disturbance are able to continue processing as long as there are engines with the corresponding state in the buffer.

To achieve the transportation between the main assembly line and the flexible buffers, the first phase also introduces docking stations at various points in the main assembly line to take off and insert engines, and a set of automated guided vehicles (AGVs) able to transport an engine pallet between docking stations and buffers.

In the second phase, the classical layout is extended by multi-functional (MF) stations able to perform the same assembly operations as a set of stations on the main assembly line. In figure 3, for example, MF01 is able to replace one or all of the stations A02 to M04, while MF-station MF02 is able to replace stations M04 to A07. The processing times of the MF-stations though are usually higher because they are operated manually.

In case of a disturbance or a bottleneck, the MF-stations can be used to replace or increase the capacity of the stations at the main line. Let's assume station A03 is slower than the other stations in the main line. The MF-station MF01 can then be used to reduce the bottleneck at station A03 if any engines waiting in front of station A03 are transported to the MF-station and after processing are inserted again after station A03.

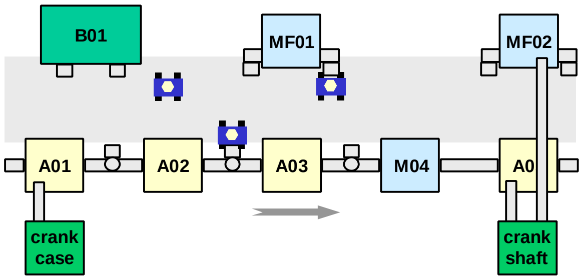

Fig. 3: Introduction of multi-functional stations (phase 2).

MF-stations can either be added to compensate a bottleneck in the main assembly line, or to increase the overall capacity of the assembly system. In the last case, an MF-station is associated with a section of the main line such that the capacity in every section is increased. Once the MF-stations are actually supposed to form an entire second line of assembly, the system enters phase three.

In phase three, the MF-stations are converted to or replaced by more dedicated assembly stations and are connected by stationary transportation elements. Engines may now be produced on two parallel assembly lines and, as a result, the production capacity of the initial assembly system is (finally) doubled. The AGVs and flexible buffers then may be used to buffer engines in case of a disturbance on either of the two assembly lines.

To summarize, the new assembly layout proposed allows to introduce buffering and processing capacities as needed. At first, the buffering and processing capacities are used to remove bottlenecks in the main assembly line. Then gradually, these additional resources are used to increase the capacity of the assembly line until the initial capacity is doubled and an entire second assembly line is installed.

4 Holonic control

The introduction of flexible buffering and processing capacities not only changes the assembly process, it also requires a more sophisticated control system. While in the classical assembly an engine has no choice but to move from one station to the next, in the holonic assembly an engine may either be processed by the next station, by one of the MF-stations, or it may be stored in one of the flexible buffers. Because of these processing alternatives, the system control must take into account global aspects during the operation. For instance, an engine should only be taken off the main assembly line in front of a disturbance or bottleneck. If it is taken off the main line before the bottleneck, the processing capacities in front of the disturbance will become unused. A system control for the holonic assembly therefore needs to coordinate the actions of different components in order to achieve a globally optimal performance.

An agent-oriented approach is ideally suited for such a control task. Agent technology provides techniques for modeling and implementing autonomous and cooperative software systems, and is thus an enabling technology for holonic manufacturing systems [5]. Agents can even be viewed as holons without physical processing capabilities [1]. To design the control system for the holonic assembly, we have therefore adopted a methodology developed for designing agent-oriented production control systems [3]. This methodology analyzes the necessary control decisions, identifies the agents by clustering control decisions, and chooses interaction techniques to resolve decision dependencies between agents by classifying the decision dependencies and matching the classification against existing interaction techniques. The result of this design process is summarized in the following.

The control system developed for the holonic assembly consists of a holon for each docking station (DS holon), each MF-station (MF holon), each engine buffer (EB holon), and each AGV (AGV holon). A DS holon decides whether (and when) to divert an engine from the main line and does so by coordinating its decision with the other docking stations. In particular, a DS holon may divert an engine only if it is closest to the next bottleneck station. Furthermore, to divert an engine a DS holon must find either an MF-station that will process the engine, or a buffer currently capable to store the engine. It does so by requesting capacity from the corresponding holons. Once it has received the required capacity, the DS holon requests an AGV to do the transportation and waits for the engine to be picked up.

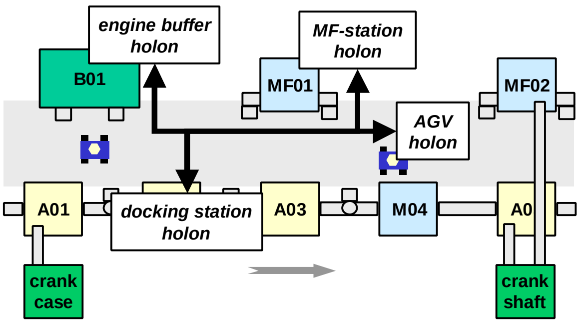

Fig. 4: Control holons.

The MF holon decides for each arriving engine where to send it to next. To do so, it requests DS holons, other MF holons, or EB holons to accept the engine for further processing (or buffering). Depending on the holon that accepted the engine, the MF-station performs the assembly operations necessary to put the engine in the correct processing state. Like the MF holon, the EB holon decides when and where to send the engine to next. Finally, the AGV holons offer their transportation capacity to any holon that requests it.

Note that an assembly station of the main line is not represented by a holon because it has no decision alternatives, i.e., it always processes an engine as soon as it arrives at the station. Note also that an engine is not represented by a holon because the holonic system is supposed to extend the existing assembly system and in the existing system engines have no computing capabilities. Not extending assembly stations and engines with holonic capabilities has the important advantage that at any time the holonic system could be turned off, while the main assembly system could still operate in the classical way. This reduces the risk of introducing holonic technology since the classical assembly system still exists as a backup.

5 Results

To evaluate the new assembly design and in particular to compare it to the existing system, the holonic assembly system was implemented in the same simulator that was used to analyze the existing system. The holonic control was implemented in a proprietary Java tool, called DARE, and connected via a socket link to the simulator so that the holons implemented in DARE were able to control the simulation components. The holonic assembly was run for a variety of scenarios, in particular the same scenarios that were used for the analysis of NVM. The main results of the simulation are reported in the following.

First of all, the holonic system showed more robust behavior than the existing assembly system. Robustness was measured by computing the productivity of a system over a long period of time (typically a week of production). Productivity is defined as the throughput of a system under disturbances divided by the maximal throughput of the system if no disturbances occur at all.

Figure 5 compares the productivity of the classical assembly system (CA), the assembly system in phase 1 with flexible buffering (FB), the assembly system in phase 2 with three MF-stations for the body assembly (3MF), and phase 2 with five MF-stations

(5MF). As the figure shows, the productivity increases by 20% when flexible buffers are introduced, and by 16% when three MF-stations are added. Thus, the holonic assembly system increases the robustness of the assembly operations significantly. However, the productivity actually decreases if more MF-stations are added (even though it is still higher than the productivity of the classical assembly systems). The productivity decreases with more MF-stations because the MF-stations are likely to become idle if their capacity (designated to a section of the assembly) is greater than the loss due to the disturbances in that section. Too many MF-stations thus create over-capacity which reduces the productivity.

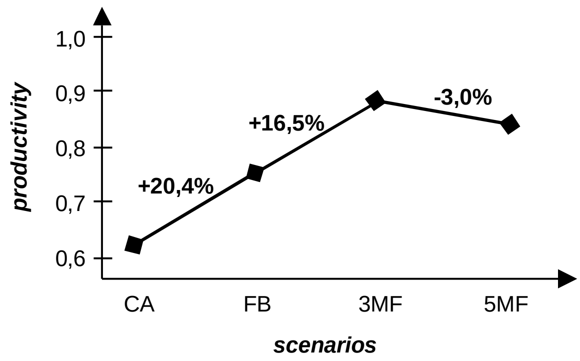

Fig. 5: Robustness.

Secondly and more importantly, the holonic system can be scaled up in steps of 20% on average (cf. figure 6). The introduction of flexible buffers not only increases robustness, but as a side effect also increases the throughput and thus scales up the volume of the assembly system. Likewise, the introduction of MF-stations increases the capacity of assembly sections and thus – if placed carefully – also increases the volume. In particular, the more MF-stations are introduced, the higher the capacity and thus the volume (however, the productivity does not necessarily increase as the volume increases, as discussed above).

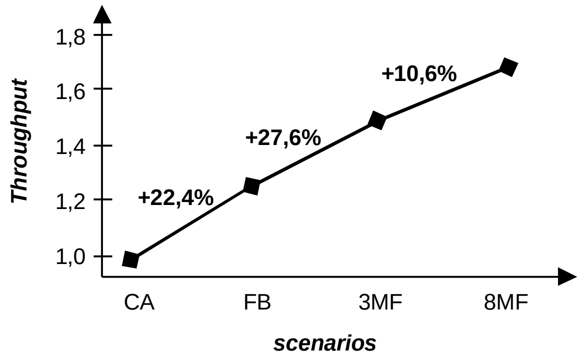

Fig. 6: Scalability.

The ability to increase the volume in steps of 20% after the system has been installed is a clear advantage of the holonic assembly over existing assembly systems. Currently, if the demand increases, the volume of the production system can only be doubled by installing an entire second production line (after any measures such as overtime and additional shifts have been taken). If the demand has increased, but not been doubled, the second line is underutilized and the overall costs per product increase. The ability to scale the volume in smaller steps (after the installation) is thus a competitive advantage that allows to satisfy the demand faster and more cost-effectively when facing a volatile market demand.

All in all, the holonic approach provides robustness and scalability which is unprecedented in existing assembly systems, while satisfying all other industrial requirements, such as high volume production, quality assurance, and low costs per product.

6 Conclusions

The holonic paradigm promises to meet the upcoming challenges of the manufacturing industry by introducing autonomous and cooperative units that drive the manufacturing process. The implementation of the holonic paradigm, however, would revolutionize current manufacturing processes and thus needs to be thoroughly evaluated before it is adopted. This paper has evaluated the paradigm by reporting on an industrial feasibility study for engine assembly.

The feasibility study has demonstrated that the holonic paradigm does meet the requirements of an industrial deployment, increasing scalability and productivity of the assembly process, while maintaining high volume and low costs per product. To our knowledge, this is also the first approach to integrate existing and holonic manufacturing concepts that allows to migrate from the traditional to a fully holonic assembly system, thus reducing the risk of introducing a completely new technology.

The deployment of holonic concepts in industrial processes though will require the availability of products for holonic control and the identification of a broader range of applications which in total will justify the development of a completely new generation of control technology. Furthermore, plant personnel has to be trained in how to operate and maintain such a kind of control technology. For this, training concepts have to be developed that guarantee the acceptance of the new concepts by the operators (and the managers). If either the products are not available, or the new technology is not accepted by the people who should use (and buy) it, the new technology will fail no matter how significant the technical benefits are. Thus, development of holonic products and training strategies are the upcoming challenges of the holonic paradigm.

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