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Modelling for Decision-making in Dynamic Line-less Assembly Systems

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Abstract

The shift towards electro mobility has a significant impact on the entire value chain of the automotive industry. The parallel production of Internal Combustion Engine, Battery Electric and Plug-in Hybrid Electric Vehicles con-fronts manufacturers with major challenges. This requires flexible production systems that are able to operate efficiently even under the influence of dynamic conditions. As could be seen in the COVID-19 pandemic, production systems must be able to react flexible and resilient even to these kinds of situations. Within the production system there is a multitude of temporally and spatially determined neuralgic points at which a reaction to dynamic conditions is possible and necessary. In order to make target-oriented decisions at these points, a large amount of data from many different sources is required as input parameters. The decisions can be made manually, semi-automatically or automatically by a human, a machine or a (software) system. Therefore it is essential that influences, input and output variables as well as decisions and the solution space are provided in a defined manner enabling all involved units to process the information. The paper therefore describes the first steps in modeling decisions for dynamic line-less assembly systems. Starting with an introduction to the topic and the multi-variant automotive production, the architecture of this kind of flexible assembly system is briefly described. Afterwards a description of the formal modeling of decisions in assembly systems is presented. Finally, after a discussion of the results, an outlook on the next steps and further research needs is given.

Keywords

assembly systems; decision-making; modelling; flexible manufacturing; smart expert system

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1. Introduction

Modern production systems are on the verge of change, as they have to adapt to constantly changing conditions. For example, the current challenges in connection with the COVID-19 pandemic show that current production systems are not or less prepared for such unexpected and severe changes. Especially the supply chain and the rigid planning of production processes is affected by these turbulences, caused by the pandemic situation. In particular, the automotive industry is faced with the challenge of satisfying the various market requirements and producing many different variants. Electro mobility is intensifying these requirements, since in addition to Internal Combustion Engine Vehicles (ICEV), Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV) must also be produced. This has a profound impact on the value chain of the automotive industry [1,2] and poses various challenges for manufacturers. For example, the growing product variance on assembly lines leads to far-reaching efficiency losses [3]. This has a major impact on production efficiency, as assembly is responsible for 50% of production time and 20% of total costs for complex products [4,5]. As the final assembly will continue to be a core competence of OEMs in the future [6], new methods of planning and control of assembly systems must be developed in order to be able to react quickly and cost-effectively to dynamic conditions [7].

One way of solving these challenges is to introduce dynamic line-less assembly systems, in which individual job routes with cycle-independent processing times are made possible by resolving temporal and spatial restrictions [8]. In contrast to classical line assembly, the assembly route is not fixed and can be adapted [9]. Simulation studies from automobile production have shown that flexible, matrix-oriented assembly enables an increase in worker utilization of up to 12 % [10]. In addition, the real-time control and the flexible routing between stations can compensate for machine failures. This significantly increases the resilience of the assembly system [11].

An essential component of such systems is decision making. Within the flexible assembly, a choice must be made between a variety of options for action. For example, a product must be rerouted in the event of a machine failure, a dynamic rescheduling must be made on the basis of the current incoming order, a decision must be made on how to proceed in the event of a defective component, or the employee must decide which step to carry out next.

To be able to make such decisions, data from a variety of systems is required. In order for the decision system to be able to process the decision problem, a uniform language is necessary. In current product systems, the challenge is that the various subsystems do not speak the same language when it comes to making decisions. This also prevents decisions from being made at other levels of the production system. This paper therefore describes a way to design decision systems and to model decisions in dynamic and flexible assembly systems.

2. Foundations on Decision-making Processes in Production Systems

Decision-making is the process of choosing between alternatives [12,13]. This is a broad field and of interest in many scientific disciplines. In the context of line-less assembly systems, we are addressing data-driven decision making systems, as postulated for example in the Cluster of Excellence "Internet of Production" (cf. [14]).

First, the data available in the company in various systems is aggregated and condensed into information. Knowledge is generated with the help of, for example, methods of data analysis and machine learning. Based on historical data, future system states are predicted and thus knowledge is generated. Finally, the generated knowledge is used to support decisions or autonomously trigger actions.

The final decisions can be made by a human, a machine, a (software) system or by collaboration of different agents. In manual decisions, an agent is only supplied with information and must make a decision himself.

In addition, there are semi-automatic decisions, where an agent is offered several alternative actions, and autonomous decisions, where the agent makes a decision directly and automatically and triggers the subsequent actions. Fig. 1 shows the formal decision-making process used for all types of decisions.

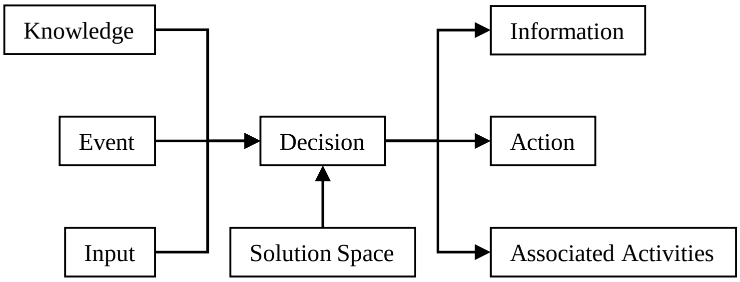

Fig. 1. Formal decision-making process (cf. [15])

The central point of the process is the *decision* itself. The best option is selected from a set of alternative actions. The exact way, the methods and the system for computing an optimal action alternative, is not within the focus of this paper. In principle, methods of operations research, machine learning and decision/game theory are applied, taking into account the probabilities and uncertainties of preceding systems and the decision system itself (see e.g. [16]).

Every decision process is triggered by an *event*. An event can be, for example, a sudden failure of a machine or a long-planned change in incoming orders. The selection of an action alternative or a decision is followed by one or more *actions* that must be performed.

In order to make a meaningful decision, the current system status (*input*) and the *knowledge* generated from past decisions are also required. The current system status contains all currently valid data of all systems and components involved in the decision process. It is therefore equivalent to a digital twin of the production system. Depending on the system design, the knowledge from previous decisions is not absolutely necessary. However, as time progresses, it supports the selection of an option for action, as the influence of measures already taken can be better assessed.

When calculating a decision, the *solution space* must also be taken into account. Without a given solution space, automated systems cannot recognize whether the calculated solution is possible and realistic. For example, without knowledge of the solution space, a system could, in the event of a new special order, increase the conveyor speed in production to an extent that is not possible, either organizationally or physically.

The output of a decision includes an action to be performed. In addition to the primary action, other secondary actions, associated activities or further information requirements may exist. For example, after a faulty component has been delivered to an assembly station, a decision may be made that the defective part should still be integrated into the vehicle (*decision*). The assembly employee is informed of this and installs the part (*action*). An exemplary *associated activity* can be that the employee marks the defective part with a color. Further *information* can be, for example, the notification of the end-of-line test and the quality assurance department about the incident.

3. System Architecture of Line-less Assembly

In order to model decisions in flexible production systems generically, comprehensively and transferable, knowledge of the superordinate system architecture is advantageous and therefore described in the following chapter.

3.1 Landscape of Involved Agents

Although the concrete landscape of these systems is heterogeneous, some commonalities can be derived and used to define a description framework. Fig. 2 shows a superordinate structure of line-less assembly agents. For a better overview, the components are arranged in the classic automation pyramid [17], even though current architectures are built on service-oriented architectures (SOA) in terms of RAMI 4.0 or comparable references [18].

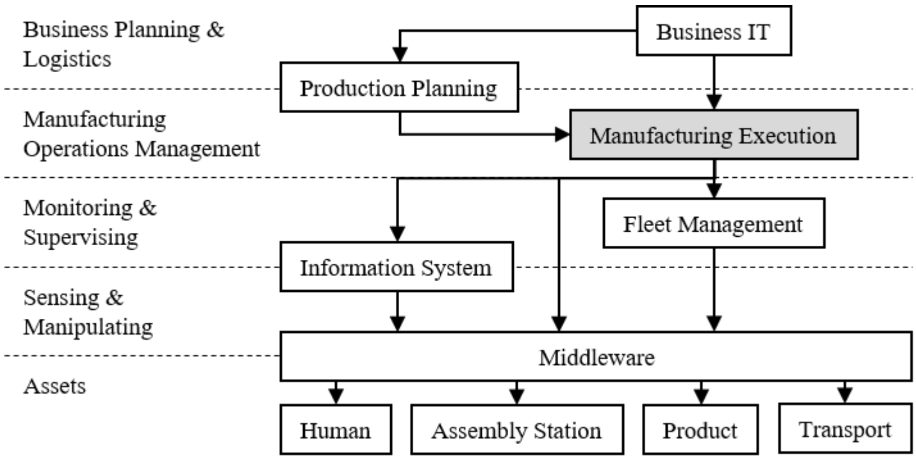

Fig. 2. Superordinate architecture of line-less assembly systems

The simplified illustration shows that a large number of systems and assets have to be linked together on different levels in order to enable flexibility and adaptation to dynamic conditions. The central element is a control system (*Manufacturing Execution*), which orchestrates the entire assembly and all agents. It receives information about e.g. product and order data from the higher-level *Business IT* systems (ERP, PLM, etc.) as well as from the *Production Planning*, which provides e.g. simulated assembly scenarios. The calculated control commands are then transmitted to the *assets* on the shop floor via a *middleware* using *information systems* and a *fleet management* system, which controls e.g. AGVs for material supply.

3.2 Modelling and Transferring Messages

Communication between the individual systems takes place via standardized service-oriented interfaces. The basis for this is an administration shell, as described in GAIA-X and RAMI 4.0. In short, the administration shell is the manifestation of the digital twin. With its help, the systems can exchange data in a structured way. The data is exchanged event-driven. Currently, systems use OPC UA, MQTT, Apache Kavka or ROS as interfaces and communication protocols [19]. What they all have in common is that they enable structured data transfer and thus interact with the administration shell. Data is transferred by applying a description-model and using markup languages like XML, AutomationML or JSON. Fig. 3 shows an abstract high-level example of a description model for resources in line-less assembly systems.

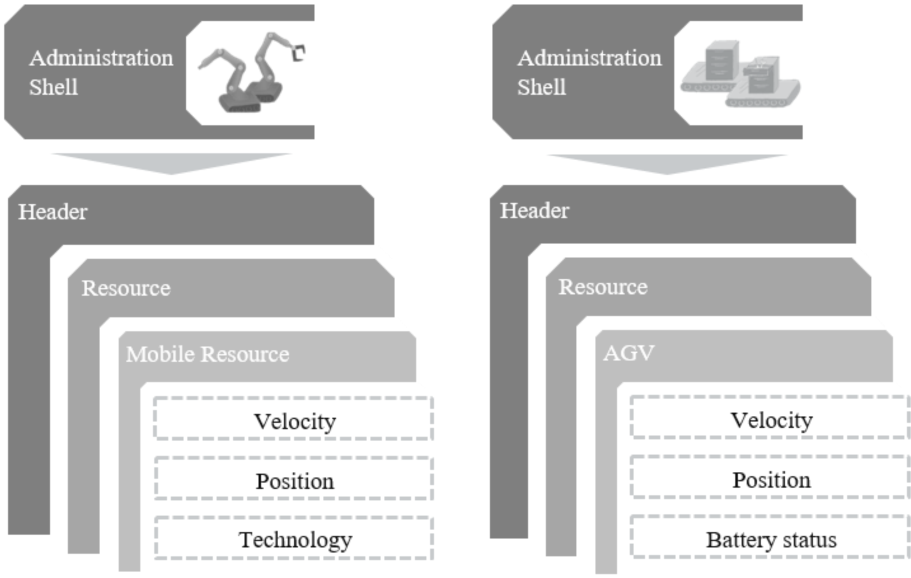

Fig. 3. Exemplary description models for resources within line-less assembly. The modular character is emphasized by a mutual usage of standardized variables (i.e. velocity & position)

The figure shows in particular the structured form of the data. The initial structuring can be very complex and extensive. Asset Administration Shells (AAS) are used to describe all resources of the production system. They contain a unified ontology. They consist of a header, which uniquely identifies the resources and contains further master data, as well as the actual user data. The user data describe the production resources, their status as well as their properties and functions. For example, a mobile robot has the properties speed and current position. The figure also shows that the structured form ensures a high degree of reusability, since an AGV, for example, shares many properties with a mobile resource.

It is also evident that these description languages can represent the entire production system in terms of data. This can be used to model the decisions, as described in the following chapter.

4. Modelling of Data-based Decisions

Based on the previous findings from chapter 2 regarding the way decisions are made and the characteristics of the system architecture of flexible assembly systems from section 3.1, the decisions finally can be modeled. It is clear that every decision process is triggered by an event. Current systems are also based on event-driven architectures. Thus, it seems reasonable to combine these two aspects, since they are based on the same principles. In industrial, especially flexible and resilient applications, several requirements for modelling decision support systems are demanded:

- Comprehensive modeling of various, even complex decisions
- Modularity and reusability of the models
- Transferability of the models to other systems and applications
- Linking of different systems on the shop floor
- Transparency, traceability and auditability of the decision made
- Integration into the existing system landscape
- Use of standardized protocols and consistent interfaces / middleware
- Inclusion of data collected in other software and machines
- Execution of actions following a decision via connected software (e.g. MES)
- Providing information and enabling both human decision support and autonomous decision making

The modeling of decisions must reflect these requirements. Since some of the requirements are already covered by the idea of the management shell, it is reasonable to use this architecture as a basis for modeling. For example, the administration shell already represents the broad use of data in terms of a digital twin or the standardized communication between cross-linked systems.

The following section shows how the decision models can be designed and integrated into existing architectures of dynamic line-less assembly systems.

4.1 Modular and Portable Decision Modelling

It is evident that the general use of the description model (see section 3.2) and the administration shell also allows the modeling and transmission of a definition of decisions. By combining all of these elements, we can model the decisions, the information needed and the actions to be taken in an equivalent form and integrate it seamlessly into existing systems. Using the Decision Model and Notation (DMN) description model and following the Predictive Model Markup Language (PMML), the neuralgic spots in production can be described as shown in Fig. 4.In the actual content of the description mode, relevant information is provided in a standardized format. For instance the dmn-context is following the DMN notation for distinctively identifying the product ID.

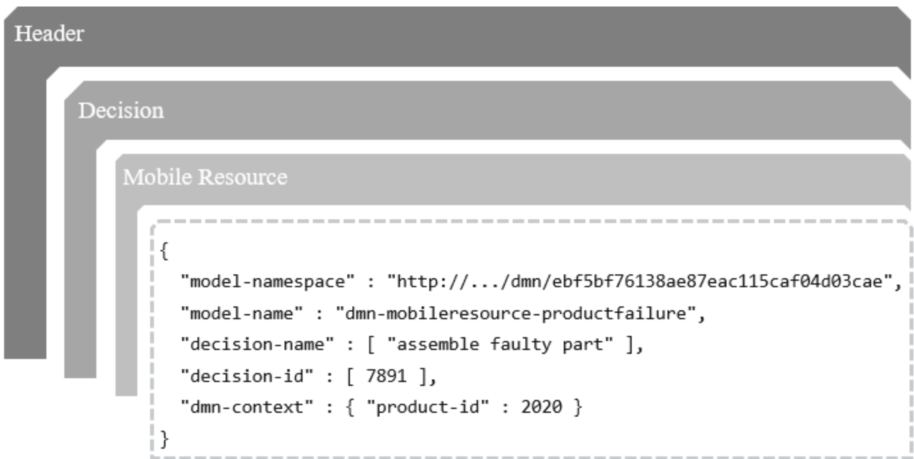

Fig. 4. Exemplary description model for decisions in line-less assembly. The integration is performed in analogy to Fig. 3 in the administration shells. Standardized variables enable modularity and portability.

The figure illustrates the similarities to Fig. 3. All required information which is essential for a decision system as described in chapter 2 is included in the administration shell. For reusability all decision models are stored in a namespace. Modularity is emphasized by clustering of decisions to models. The decisions are modeled in DMN's FEEL language. This allows to model complex decision systems. The human-readable FEEL language secures the transparency of the decisions. This allows automated decision systems to be certified and used in a broad application field.

4.2 Categorizing and Prioritizing Dependent Decisions

After modeling decisions, it is important to categorize and prioritize the different decisions. The background is that an action triggered after a decision can trigger a new event and thus a new decision and action. The order in which decisions are processed is thus elementary so that the production system does not block or even self-lock completely.

This can be illustrated with an example. Let us assume that a production resource fails. This triggers an error event, which is picked up by the MES system, for example. The MES system plans a new route for the product. An additional AGV is required to transport the product and is no longer available for other orders.

The delay also triggers an event in the planning system, which has to adjust the medium-term planning. And this in turn leads to changes at the station level. Many of these decisions take place in short intervals and are executed by different agents influencing each other. Referencing Fig. 2, decisions can be assigned to the levels of the automation pyramid. Often decisions on higher levels have more weight, because many subsequent systems also have to react to these decisions. On the other hand, decisions at this level tend to have a longer time horizon, so that in extreme cases both effects may cancel each other. A further limitation is offered by the described systematics according to the degree of automation. Manual decisions involve greater uncertainty and are therefore more relevant to the decision-making system. In order to process such influences, influencing and target criteria are necessary, which systematize the various, sometimes conflicting requirements. The previously made classifications alone are not sufficient for modern production systems, because they disregard the time factor, for example. In order to give companies and decision-making systems a simple and practical way to prioritize the many different decisions in dynamical line-less assembly systems, we propose the introduction of a Decision Priority Number (DPN). Based on the Risk Priority Number as known from Failure Mode and Effects Analysis (FMEA), this can be defined as follows:

$$DPN = I \times F \times C \qquad I, F, C \in [0, 10] \tag{1}$$

The DPN compares different decisions according to their priority. A larger DPN means a higher priority. The three influencing factors are briefly described below.

Impact *I*. Describes the effects on the partial or complete system. Specifies the complexity of the decision respectively the scope of the consequences that are triggered by a decision. Depends significantly on the type and level of the decision-making process. Decisions at a higher level tend to have a greater impact on the global system.

Frequency *F*. Shows how often and how regularly a similar decision must be made. A higher frequency and regularity implies a higher relevance. However, it is also possible that a more frequent, irregular occurrence of the event points to a more general and therefore more important problem.

Criticality *C*. Indicates the criticality of a decision, especially with regard to time. In general, decision-making processes with a shorter time horizon are considered more critical.

5. Conclusion and Outlook

By unifying current systems architectures and methods, decision theory, and the use of service-oriented and event-based agents, it could be shown that calculated decisions can be modeled without restrictions and can be seamlessly integrated into existing systems in line-less assembly. The paper demonstrates the combination of existing modeling tools and current architectures of flexible assembly systems and how decisions can be integrated into these administration shells without major side effects, such as manually modelling and adjusting the overarching structure. The direct benefit and practical value is the faster integration of corresponding decision models for new resources or changes in products or processes. A unique feature of this work is combination of asset administration shells with the decision modelling paradigms, which enables for interoperability and compatibility with other asset administration shell based data modelling approaches.

Particularly problematic is the high complexity of the overall system and the prioritization of decisions. Therefore, possibilities for the categorization of various events were shown. Primarily, there is a need for further research on the following aspects:

- Development of a catalog for decision-making in manufacturing companies
- Systematization of decisions
- Handling of probabilities and uncertainties

- Practical validation of decision prioritization
- Development and verification of agent-based software systems for delegating decision-making processes
- Practical review and adjustment

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References

[1] PWC, 2018. The turning of the tide. Impacts of the automotive transformation on the value chain.: PWC Autofacts.

[2] Seeberger, M., Dyllick, T., Stölzle, W., 2016. Der Wandel in der Automobilindustrie hin zur Elektromobilität– Veränderungen und neue Wertschöpfungspotenziale für Automobilhersteller. St. Gallen.

[3] Kampker, A., 2014. Elektromobilproduktion. Springer-Verlag.

[4] Hu, S.J., Ko, J., Weyand, L., ElMaraghy, H.A., Lien, T.K., Koren, Y., Bley, H., Chryssolouris, G., Nasr, N., Shpitalni, M., 2011. Assembly system design and operations for product variety. CIRP annals 60 (2), 715–733.

[5] Lotter, B., Wiendahl, H.-P., 2013. Montage in der industriellen Produktion: Ein Handbuch für die Praxis. Springer-Verlag.

[6] Deloitte, 2017. The Future of the Automotive Value Chain. 2025 and beyond.

[7] Göppert, A., Grunert, D., Hüttemann, G., et al., 2019. Frei verkettete Montage von Elektrofahrzeugen, in: Tagungsband der 1. Stuttgarter Tagung zur Zukunft der Automobilproduktion.

[8] Grunert, D., Jung, S., Leipold, T., Göppert, A., Hüttemann, G., Schmitt, R., 2019. Service-oriented Information Model for the Model-Driven Control of Dynamically Interconnected Assembly Systems, in: , Tagungsband des 4. Kongresses Montage Handhabung Industrieroboter. Springer, pp. 23–33.

[9] Hees, F., Müller-Abdelrazeq, S., Voss, M., Schmitt, R., Hüttemann, G., Rook-Weiler, K., Herfs, W., Roggendorf, S., Heinen, K., Kuhlenkötter, B., 2019. Projektatlas Kompetenz Montage: kollaborativ und wandlungsfähig. RWTH Aachen University, Lehrstuhl für Informationsmanagement im Maschinenbau.

[10] Küpper, D., Sieben, C., Kuhlmann, K., Lim, Y.H., Ahmad, A., 2018. Will Flexible-Cell Manufacturing Revolutionize Carmaking. BCG: https://www. bcg. com/de-de/about/impressum. aspx.

[11] Göppert, A., Rachner, J., Schmitt, R.H., 2020. Automated scenario analysis of reinforcement learning controlled line-less assembly systems. Procedia CIRP 93, 1091–1096.

[12] Cambridge Academic Content Dictionary, 2020. Decision-making.

[13] Oxford Learner's Dictionary, 2020. Decision-making.

[14] Pennekamp, J., Glebke, R., Henze, M., Meisen, T., Quix, C., Hai, R., Gleim, L., Niemietz, P., Rudack, M., Knape, S. Towards an infrastructure enabling the internet of production, in: 2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS). IEEE, pp. 31–37.

[15] Object Management Group, 2020. Decision Model and Notation.

[16] Lepenioti, K., Bousdekis, A., Apostolou, D., Mentzas, G., 2020. Prescriptive analytics: Literature review and research challenges. International Journal of Information Management 50, 57–70.

[17] ANSI/ISA 95, 2013. Enterprise-Control System Integration.

[18] DIN SPEC, 2016. Reference Architecture Model Industrie 4.0 (RAMI4.0).

[19] Schmitt, R.H., König, N., Jung, S., et al., 2020. Architektur einer vernetzten, adaptiven Produktion, in: Aachener Werkzeugmaschinen-Kolloquium: Internet of Production – Turning Data into Value, pp. 4–19.

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