Modelling Capabilities for Functional Configuration of Part Feeding Equipment

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Abstract

This paper introduces a configuration framework for automatic configuration of production systems. The proposed framework consists of three key aspects; 1) functional configuration, 2) interface configuration and 3) behavioral configuration, that together offers the ability to automatically identify production resources, and aggregate them to form a production system. The main focus of this work is to model functional capabilities to facilitate automatic suggestion of part feeding resources, and exemplifies different approaches to model part feeding capabilities.

1. Introduction

   Due to decreasing product life cycles and increasing demand for product variants in low volumes, changeability has become a vital requirement for current production systems [1]. Important aspects for developing changeable production systems are that production resources can be rapidly (re-)configured and deployed to accommodate

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changing requirements. This involves the abilities to rapidly identify feasible production system solutions, rapidly add and/or remove production resources to/from the layout, and rapidly program or configure the control logics of the resources and the production system as a whole [2]. While research within reconfigurable and evolvable production systems has progressed the development of modular and intelligent resources that can be rapidly reconfigured and deployed [3,4], designing such resources and configuring production system solutions still remains a time-consuming activity [5]. Configuration of production systems involves solving certain design aspects such as identifying relevant production resources that can be utilised, investigating whether the resources are compatible with one another, layout of resources in combination, and verification and design optimisation of resources to ensure production of a product [6,7]. To address the challenge of bringing changeability to production systems, there is a need to develop methodologies, information models and tools for facilitating rapid configuration of production systems in terms of automating the process of selecting production resources and aggregating systems out of them.

One type of production equipment that could greatly benefit from automatic configuration is part feeding equipment. For assembly production, the term part feeding is used to describe equipment that handles two separate, but closely connected process tasks, which consist of; part structuring and part presentation. Part structuring concerns the process of singulating individual parts from a bundle of parts, and arranging individual parts from having a random orientation towards a known orientation. Part presentation concerns the process of moving an individual structured part to a predetermined location. There exist a vast range of resources that can be applied for part feeding, but in general they can be divided into four different categories; mechanically based part feeders, flexible part feeders, bin picking part feeders, and magasine part feeders [8].

The research for this paper focuses on the specific configuration aspect of how to enable automatic identification of part feeding solutions (henceforth referred to as functional configuration). According to Lohse and Ratchev [9], the development of a method for functional configuration needs to address two challenges. The first challenge is to define knowledge models that describe the functionalities of a resource on a required level of detail so that it can be used in the configuration process. The second challenge is to formalise methods and algorithms that can be used to automate the configuration process in terms of matching production resources against product requirements.

In this paper, we will address the first challenge where the main focus is on the task of modelling functionalities of part feeding resources to enable functional configuration. In Section 2, a framework for automatic configuration of production systems is presented to describe the role and requirements for functional configuration. In Section 3, we will review related work on how to conduct functional configuration. In Section 4, a capability-based approach for functional configuration is elaborated, and in Section 5, we will address how to model functional capabilities of part feeding resources to enable functional configuration using the capability-based approach.

2. Production System Configuration Framework

Before we address how functional configuration can be conducted, it is necessary to understand the context and role this specific configuration aspect has in the process of configuring a production system. Fig. 1 illustrates the proposed framework for production system configuration and consist of three configurational aspects: functional configuration, interface configuration and behavioural configuration. The outset for automatic configuration of production systems is that a set of candidate resources can be identified (functional configuration). Furthermore, in order to validate if the candidates in combination are suitable for producing a specific product, the configuration process needs to validate both if the resources are structurally compatible (interface configuration) and if they are able to fulfill the desired behaviour for the specific production context (behavioural configuration). This of course requires that product requirements and resources are described according to the information needed for each of the configuration aspects.

In order to initiate the functional configuration process, the requirements for a solution need to be specified in terms of required functionalities, and resources need to be described according to the functionalities that they provide. For production equipment, functionalities are used to describe the capabilities of a resource that can be utilised for a specific purpose. For example, part feeding equipment can be described as having the capabilities to structure and present parts, which are capabilities that can be utilised to conduct the process of part feeding (as described in Section 1). Functional configuration is initiated by a product requirement specifying a set of processes that are needed to produce a product (e.g. part feeding, pick and place, milling and drilling). Identification of
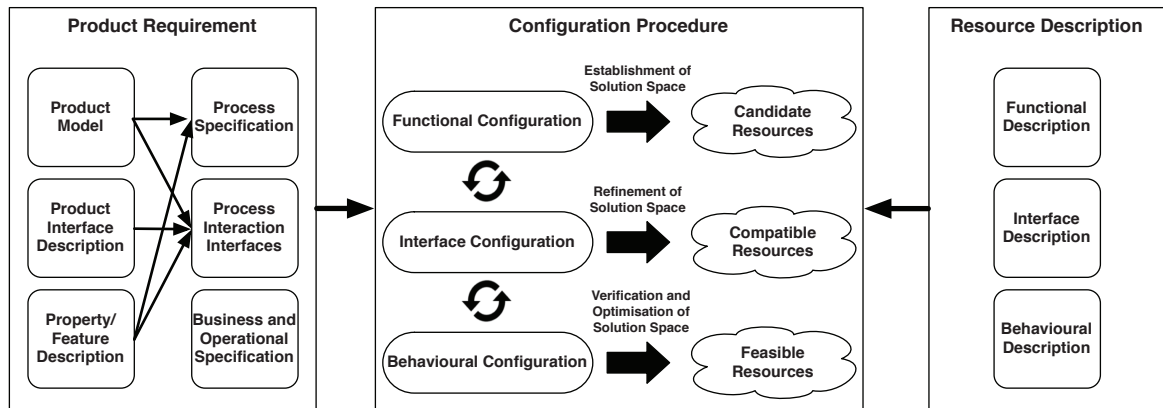
Figure 1 - Framework for configuration of production system

resources is then conducted by searching for resources that offers the required functionalities to perform each of the processes. As soon as a collection of resources has been identified that provides all of the required functionalities, it is categorised as a candidate solution to produce the product.

After the functional configuration has found and grouped resources into candidate solutions, the interface configuration can be initiated, where it has two purposes that have to be fulfilled. The first purpose of the interface configuration is related to the layout and compatibility of a solution. For example, there should be a reasoning mechanism to validate if a gripper can be structurally combined with a robot, and that the robot is not placed outside of reach for placing a product part into a fixture. Another purpose of the interface configuration is to establish a specification of the desired interaction between resources. For example, if a robot with a gripper has to pick a part from a part feeder and place it in a fixture, the fixture itself will utilise a specific set of geometrical interfaces on the part. The fixture will then dictate the available part interfaces that a gripper may utilise, which in turn dictate the interfaces that should be accessible after the part has been fed from the part feeder. These chains of interaction interfaces between resources and a part are necessary to establish because they further specify spatial requirements that may affect the design of resources.

After the interface configuration has filtered out resources that cannot be structurally combined and has established interaction interface specifications, the resources' behaviour can be configured. A resource's behaviour can be viewed as a transformation system, where a resource will change the state of a part after interaction. The task for the behavioural configuration is to; 1) verify that the state of a part is transformed according to requirements, and 2) optimise the design of a resource until a/the desired state is achieved and the operational requirements are met (e.g. cycle-time and throughput). This of course requires that numerous design scenarios can be tested, which requires that simulation- and optimisation methods are utilised to guide the behavioural configuration process. An example of how behavioural configuration can be conducted for a vibratory bowl feeder is described by Hansson et al. [10]. For processes that change a part's geometrical structure (e.g. milling, drilling and welding), a specification of input state and desired output state needs to be defined as part of the product requirements in order to conduct behavioural configuration of resources that perform such processes. For logistical processes (e.g. part feeding and transportation), the changes of state are primarily related to spatial changes. As mentioned previously, these are specified according to the interaction interface specification, since such state description needs to be reasoned between multiple resources in relation to a part.

3. Related Work

As mentioned in Section 1, the focus of this paper is on how to model capabilities that can be utilised to conduct functional configuration of part feeding systems. In the following, we will briefly go through different methodologies for modelling functional capabilities.

Kitamura et al. [11, 12] present an ontological model to describe device functions on the basis of a Function-Behaviour-Structure (FBS) framework. The structural layer is used to describe the decomposition of devices/resources, which are mapped to the behaviours that each device offers. Functions are described as a specific utlisation of behaviours, to which the same behaviours can be described as offering different functionalities, depending on the purpose they are used for. Since their primary focus for the framework has been on how to conduct functional modelling of devices and how such modelling could be used as a communication tool between engineers, the discussion of how their model could be integrated into a configuration process is limited.

Lohse [13] describes an ontological framework that proscribes how to model the domains of products, processes and production equipment, and their interrelations. The modelling of production equipment has also been according to a FBS approach. The framework's initial purpose was to facilitate an easier process for system integrators to select and configure production equipment. Although not focusing on the implementation of methods for automatic configuration of production systems, Lohse argue that the models are developed to be incorporated in such process.

Järvenpää et al. [14] have developed an ontology-based Capability Model, which is used to describe the capabilities of production resources. The representation includes the capability name and the parameters related to the specific capability. The model builds links between simple and combined capabilities, and therefore allows the automatic identification of potential resource combinations for certain product requirement represented on a combined capability level.

Pfrommer et al. [15] describe a skill-based framework that models the relation between products, processes and resources. Skills are used to describe functionalities of resources that can be used to conduct production processes. Furthermore, skills can be mapped to control logic, e.g. PLC- and robot programs, that specifies how a skill is achieved for a specific resource. Skills can be used to formulate tasks, which describes how a product should be produced. However, the discussion on how resources are identified is limited, since the focus primarily is on rapid deployment of resources.

Antzoulatos et al. [16] describe a framework for plug-and-produce production, where automatic identification of required resources can be derived from product specifications. Resources are described according to functional capabilities, and uses specific rules to match a product specification against capabilities. Each capability can be translated to coherent control logic, so that rapid deployment of the resource can be facilitated.

Most of the available approaches presented above are developed for specific domains with limited focus on how the functional capabilities of part feeding resources can be modelled. Furthermore, since the primary focus has been on establishing the methodologies, limited attention has been on describing different modelling approaches and how they influence the automatic identification of resources.

4. Functional Configuration using a Capability-based Approach

In this paper, the outset for conducting functional configuration is by using a capability-based modelling and matchmaking approach [14]. As illustrated in Fig. 2, the basis for the capability-based approach is a capability model that describes how capabilities are combined and how they can be utilised to perform certain production processes. Resources are described according to the capabilities they provide, and product requirements specifies the required processes needed to produce a product. Thereby, a relation between resources and product requirements can be established by utilising the capability model as a matchmaking protocol and a search tree for identifying candidate resource combination.

In the following, the basic concept behind the capability model will be described, along with how it can be used as a basis for conducting a matchmaking procedure. How the matchmaking process is specifically conducted is out of the scope of this paper, but is explained with more details in Järvenpää et al. [17].

Product Requirement   **Functional Configuration**   **Candidate Resources**
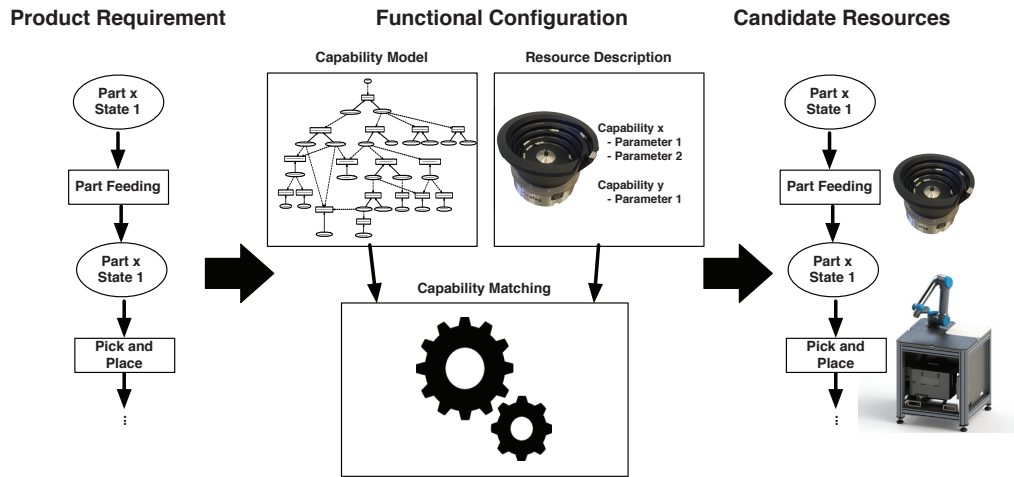

Figure 2 - The principle for functional configuration using a capability-based approach

The capability model is a knowledge model for describing the functionalities that resources provides in terms of capabilities (such as moving and grasping). Furthermore, to create a mapping between resources and product requirements, processes are defined according to the required capabilities needed to realize the process. As illustrated in Fig. 3, capabilities can be divided into two types; simple capabilities and combined capabilities. Simple capabilities are lower level capabilities that can be assigned to resources. Combined capabilities are upper level capabilities that are derived by combining multiple capabilities. In order to specify how combined capabilities are established, both simple and combined capabilities can be defined to provide capability associations, and combined capabilities can be defined according to required capability associations. Combined capabilities are primary used to manage capabilities that derives from co-operating resources, but can also be used to decompose capabilities into a hierarchical structure.
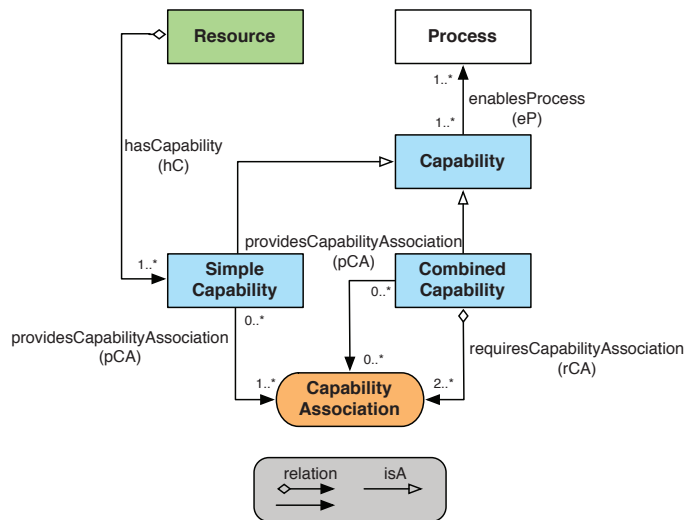

Figure 3 - The primary concepts and relations of the capability model
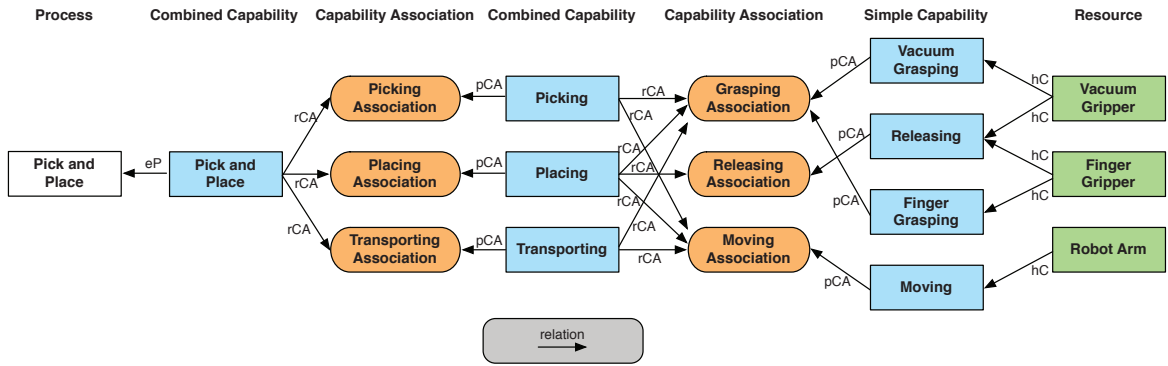
Figure 4 - Example of capabilities and capability associations for defining a pick and place process, and the linking to relevant resources

Fig. 4 shows an example of a capability model that can be used to identify resources that can conduct a *Pick and Place* process. Here, *Pick and Place* is specified as requiring the capabilities of *Picking*, *Placing* and *Transporting*, which are combined capabilities that each requires specific capability associations. For instance, in order to pick a part, the system needs to be able to move to a specific location and grasp a part. This is captured by specifying that a *Moving Association* and a *Grasping Association* are required. There may be multiple capabilities that offers such capability association, for instance, both the *Vacuum Grasping* and *Finger Grasping* capabilities offers a *Grasping Associations*, to which the capability model can be used to capture different resources that can be used to pick an item. Through this specific example of the capability model, two candidate solutions for a pick and place process can be identified; a robot arm with a vacuum gripper and a robot arm with a finger gripper.

5. Capability Modelling of Part Feeding Equipment

In this section, we will investigate how a model can be established to enable functional configuration of part feeding resources. As an example, Fig. 5 depicts the main identified capabilities of two different types of part feeding resources; a vibratory bowl feeder (mechanically based part feeder) and a flexible feeder. As mentioned in Section 1, part feeding processes can generally be described to handle two tasks; part structuring and part presentation. In the following, only capabilities related to part structuring processes have been modeled for the part feeding resources. Capabilities should of course be defined on the granularity level on which the configuration and
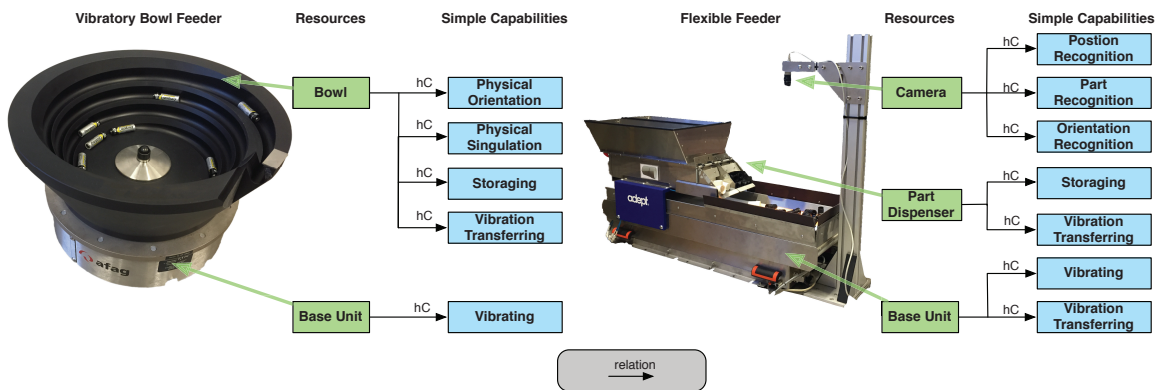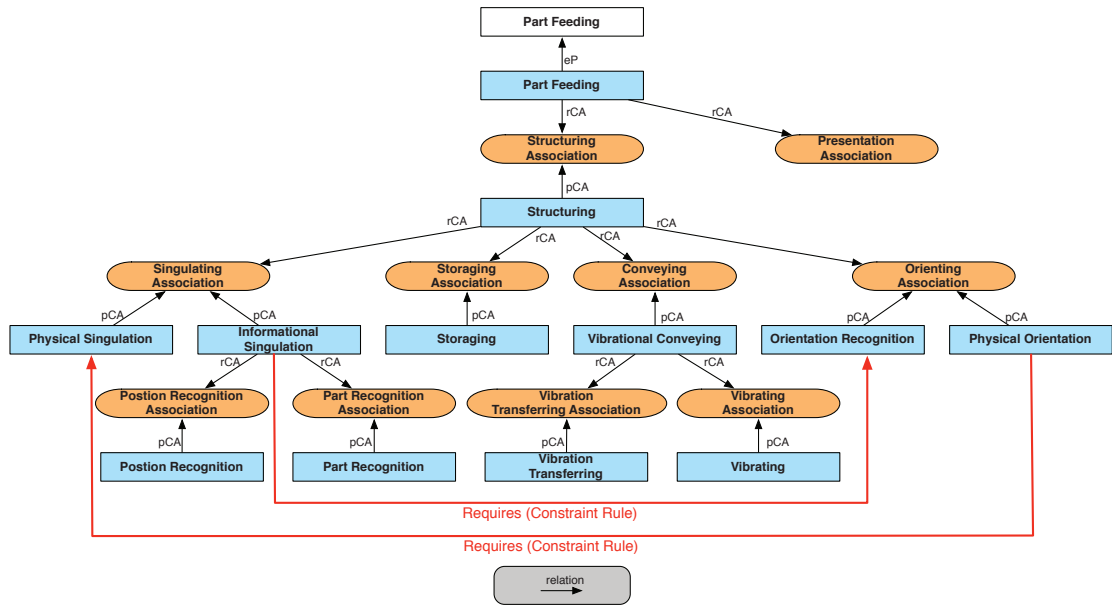

Figure 5 - Capabilities of part feeding resources

Figure 6 - Capability modelling of part feeding resources according to an accumulative approach

reconfiguration should take place. In Fig. 5, the vibratory bowl feeder is assumed to consist and be configured from a bowl and base unit, and therefore the capability model needs to have relevant capabilities for these resource entities. If the base unit of the vibratory bowl feeder was chosen to be described as consisting of resources such as spring packs and driving coils, the capabilities would also be required to be described at a finer granularity level in order to enable functional configuration.

Fig. 5 illustrates the capabilities from the resources individual perspective, but in order to facilitate functional configuration, it is necessary to define a capability model that captures that both a vibratory bowl feeder and a flexible feeder are candidate resources to perform part feeding. There are different approaches to defining a capability model, each having specific advantages and disadvantages. In the following, three different approaches will be exemplified: an accumulating approach, a back-tracking approach, and a technological approach.

Fig. 6 depicts a capability model using the accumulative approach. Here the focus is to model capabilities from a bottom-up perspective by focusing on each individual capability and how capabilities are accumulated to form other generic capabilities. The advantage of using this approach is that capabilities offering similar functionalities can easily be defined as alternative implementations. The disadvantage is that capability constraints are not captured by the capability model and needs to be incorporated as additional constraint rules in the matchmaking procedure. For instance, in order to physically orient a part, it requires that a constraint rule is defined to capture that the capability *Physical Orientation* only can be selected in combination with *Physical Singulation*.

Fig. 7 shows a capability model using the back-tracking approach. Here the focus is to model capabilities from a top-down perspective, where capabilities are structured according to the reverse sequence of a process. The advantage of using this approach is that the approach seeks to differentiate different technological implementations (vibratory bowl feeding vs. flexible feeding) at an early stage, and thereby removes the need for establishing constraint rules to capture dependencies between different capabilities. The disadvantage is that adding new technological implementations of part feeding resources may need substantial changes of the model. For example, adding bin picking capabilities requires that the capability *Informational Structuring* is reformulated to capture that a *Conveying Association* only is required for flexible part feeders.

Fig. 8 illustrates how a capability model would be formed using the technological approach. Here the focus is to model capabilities according to the different technological implementations. The outset for this approach is that each
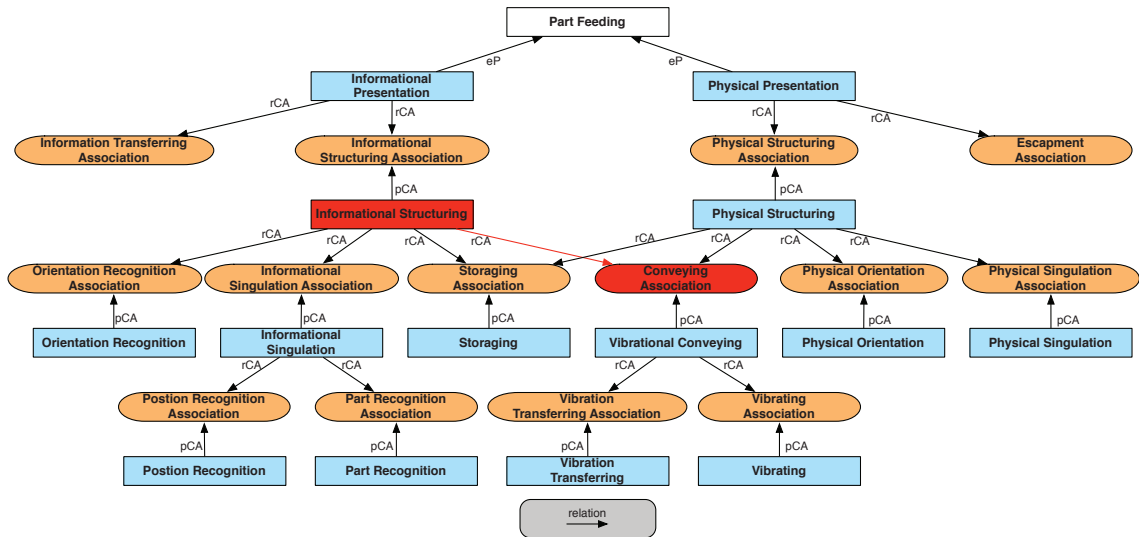
Figure 7 - Capability modelling of part feeding according to a back-tracking approach

technological implementation is defined as a specialised capability that enables part feeding. Furthermore, each feeding capability is defined as conducting the task of part structuring and part presentation, and thereby only capabilities that specifically handles these functionalites are required to be associated with the part feeding capabilities. The advantage of using this approach is that the incorporation of new part feeding technologies can be added without having to rationalise how it differs from previously modeled technologies. The disadvantage is that the specialized capabilities acts more as a classification, rather than generic capabilities that can be used for describing the capabilities of other resources.

As can be seen from the presented examples for modelling part feeding capabilities, the approaches differ in terms of maintainability and requirements for the matchmaking procedure. The accumulative approach is useful for modelling capabilities that have similar purposes, but requires that additional constraint rules are specified between capabilities in order to filter out resources that cannot be functionally combined. The back-tracking approach is able to capture these constraints directly in the capability model, but is not suited for continues addition of new
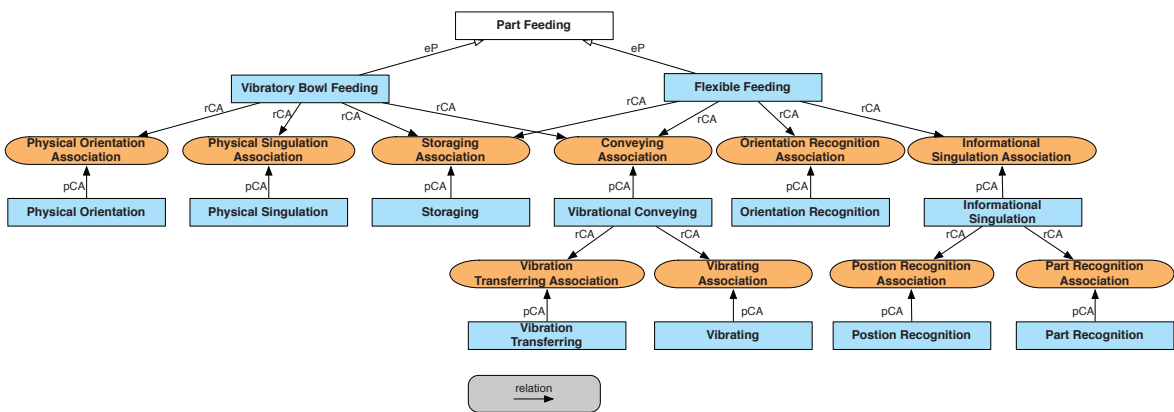
Figure 8 - Capability model of part feeding resources according to a technological approach

technological implementations of resources. The technological approach is able to both capture constraints between capabilities and enables continues incorporation of new technological implementations of resources, since the approach seeks to model such technologies independently from each other.

6. Conclusion

In this paper, a framework for automatic configuration of production systems has been presented. The framework introduces three different configuration aspects that cover how production resources can be identified, and how the configuration process can be conducted to aggregate them into production systems. The presented framework is expected to increase the responsiveness of production companies, in terms of reducing the development time of production systems.

The primary focus of the paper is to describe how automatic identification of part feeding resources can be conducted, for which a capability-based matchmaking procedure is used to conduct the identification of candidate resources. The basis for the procedure is the definition of a capability model, to which various approaches to model part feeding capabilities have been presented. Through the examples provided in this paper, the technological approach is argued to be a suited approach for modeling part feeding capabilities, since it enables the modelling of constraints between capabilities and offers continuous incorporation of different part feeding resources. Future work will be focused on expanding the capability model for part feeding, together with implementation of the matchmaking procedure. Furthermore, since the modelling approaches only been used to model part feeding resources, further research has to be conducted to verify the approaches against other types of resources.

Acknowledgements

References

[1] ElMarghy, H.A. (Ed.), Changable and Reconfigurable Manufacturing Systems, Springer, 2009
[2] Bi, Z.M., Lang, S.Y., Shen, W. & Wang, L., Reconfigurable Manufacturing Systems: The State of the Art, Int. J. of Production Research, 46(4), 2008, pp. 967-992
[3] Bi, Z.M., Lang, S.Y., Verner, M. & Orban, P., Development of Reconfigurable Machines, The Int. J. of Advance Technology, Vol. 39, Issue 11-12, 2008, pp. 1227-1251
[4] Onori, M., Lohse, N., Barata, J. & Hanisch, C., The IDEAS Project: Plug & Produce at shop-floor level, Assembly Automation, Vol. 32, Issue 2, 2012, pp. 124-134
[5] Yin, Y.H., Nee, A.Y.C., Ong, S.K., Zhu, J.Y., Gu, P.H. & Chen, L.J., Automating Design with Intelligent Human-Machine Integration, CIRP-Annals – Manufacturing Technology, Vol. 64, Issue 2, 2015, pp. 655-677
[6] Rampersad, H.K., Concentric Design of Robotic Assembly System, J. of Manufacturing Systems, Vol. 14, Issue 4, 1995, pp. 230-243
[7] Zha, X.F., Du, H & Lim, Y.E., Knowledge Intensive Petri Net Framework for Concurrent Intelligent Design of Automatic Assembly Systems, Robotics and Computer-Integrated Manufacturing, Vol. 17, Issue 5, 2001, pp. 379-398
[8] Boothroyd, G., Assembly Automation and Product Design, 2nd ed. CRC Press, 2005
[9] Lohse, N., Ratchev, S. & Chrisp, A., Function-Behaviour-Structure Model for Modular Assembly Equipment, In Proceedings of the International Precision Assembly Seminar, 2004
[10] Hansson, M.N., Mathiesen, S., Ellekilde, L.P. & Madsen, O., Configuration System for Simulation Based Design of Vibratory Bowl Feeders, IEEE International Conference on Simulation, Modeling, and Programming for Autonomous Robots (SIMPAR), 2016, pp. 147-154
[11] Kitamura, Y., Koji, Y. & Mizoguchi, R., An Ontological Model of Device Function: Industrial Deployment and Lessons Learned, Applied Ontology, Vol. 1, Issue 3-4, 2006, pp. 237-262
[12] Kitamura, Y. & Mizoguchi, R., Ontology-Based Systematization of Functional Knowledge, J. of Engineering Desing, Vol. 15, Issue 4, 2004, pp. 327-351
[13] Lohse, N. Towards an Ontology Framework for the Integrated Design of Modular Assembly Systems, Nottingham: University of Nottingham, 2006
[14] Järvenpää, E., Siltala, N. & Lanz, M., Formal Resource and Capability Descriptions Supporting Rapid Reconfiguration of Assembly Systems, In Proceedings of the International Symposium on Assembly and Manufacturing, IEEE, 2016, pp. 120-125

[15] Pfrommer, J., Schleipen, M. & Beyerer, J., PPRS: Production Skills and Their Relation to Product, Process, and Resource, IEEE 18th Conference on Emerging Technologies & Factory Automation (EFTA), 2013, pp. 1-4

[16] Antzoulatos, N., Rocha, A., Castro, E., de Silva, L. Santos, T., Ratchev, S., & Barata, J., Towards a Capability-Based Framework for Reconfiguring Industrial Production Systems, IFAC-PapersOnLine, Vol. 48, Issue 3, 2015, pp. 2077-2082

[17] Järvenpää, E., Siltala, N., Hylli, O. & Lanz, M., Capability Matchmaking Procedure to Support Rapid Configuration and Re-Configuration of Production Systems, Submitted for Publication in 27th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM), 27-30 June 2017, Modena, Italy