Automation of Intralogistic Processes through Flexibilisation
A Method for the Flexible Configuration and Evaluation of Systems of Systems

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Abstract: The high system flexibility necessary for the full automation of complex and unstructured tasks leads to increased technological complexity, thus to higher costs and lower performance. In this paper, after an introduction to the different dimensions of flexibility, a method for flexible modular configuration and evaluation of systems of systems is introduced. The method starts from process requirements and, considering factors such as feasibility, development costs, market potential and effective impact on the current processes, enables the evaluation of a flexible systems of systems equipped with the needed functionalities before its actual development. This allows setting the focus on those aspects of flexibility that add market value to the system, thus promoting the efficient development of systems addressed to interested customers in intralogistics. An example of application of the method is given and discussed.

1   INTRODUCTION

The interconnectivity of systems promoted by the fourth industrial revolution (industry 4.0), based primarily on the real-time availability of digital process information (such as position of goods throughout a facility), paved the street for the increasing adoption of service robots in the logistic sector. According to projections for the 2017, worldwide sales of robotic systems in intralogistic - defined as the organization, control, execution and optimization of the internal material and information flows and the material handling in industry, trade and public institutions (Arnold, 2006) - are estimated to increase by 46% in respect to the previous year, reaching the 37.000 units for a value of about US$ 1,2 billion (IFR, 2017). A large share of this positive trend in sales is due to the growing use of AGVs (automated Guided Vehicles) in manufacturing and partially non-manufacturing environments (Fraunhofer IPA, 2017), displaying a first and

obvious result of the interconnectivity of systems provided by the concept of industry 4.0. However, the total worldwide revenue of service robots for professional use in logistics in 2016 (US$ 992 millions) amounts only to about 7,6% of the total worldwide revenue of industrial robots in the same year (US$ 13,1 billion) (IFR, 2017). The potential for service robots in intralogistics application is still huge. On the one hand, the growth of the logistic sector, conveyed by the boom of the E-Commerce, demands for automation of more than the transport itself (AGV). On the other hand, advancements in perception, decision-making and robot abilities make it technically possible to automate handling and manipulation processes for a large variety of items. Despite these two converging factors, robotics struggles to fulfil its potential in intralogistic applications (Hägele, 2012), because the benefits of using robotics for the automation of the material handling in intralogistics not always justify the costs of a robotic solution (Bonini, 2015). As a result, the

need for efficient automation of some still manual intralogistic processes remains largely unanswered. On the one hand, potential users, seeking automation of some currently manual intralogistic processes, would rather buy technologies that are flexible, as the capacity of flexible systems can be better exploited, for a shorter investment payback period. On the other hand, technology providers would rather design their components to be flexible in order to be applicable in different domains, products and processes, as some of their fully mature technologies struggle to find their way to market or do not total enough sales to justify their development costs. However, the desired flexibility comes together with an increased level of complexity and therefore generally with (1) increased costs and (2) decreased performance, two factors potential users seeking automation of logistic processes vigorously reject.

In order to solve this issue, research should address two topics simultaneously. On the one hand the costs of flexibility should be reduced by easing the integration effort of existing software and hardware technologies through a modular approach. On the other hand, a method should be developed that enables first the flexible configuration of a system of systems (SoS from here onwards) through the aforementioned technological modules and then its evaluation before the actual development. This would in turn prevent the development of systems no investor wants to buy (high costs and low performances), thus promoting the efficient development of systems addressed to interested customers in intralogistics.

After an introduction to flexibility and its dimensions, this paper presents the aforementioned method for flexible configuration and evaluation of a SoS. The method is explained and an example of its possible outcomes is given and discussed.

2 DIMENSIONS OF FLEXIBILITY

In order to translate the general need for flexibility into a more specific requirement of "what" should be flexible and "to what extent", we propose in this section a novel taxonomy of flexibility. This is then used in the second step of the proposed method (translation into requirements), in order to focus the type of flexibility required by potential customers. Three dimensions of flexibility are identified: process, system and technological flexibility.

2.1 Process Flexibility

The dimension of process flexibility concerns the variety of processes, tasks and resources a SoS is capable of coordinating and executing.

2.1.1 Resources Allocation

One of the challenges of contemporary process management technology is the provisioning and allocation of resources for process execution, hence everything that is needed to execute a process, including machines, knowledge, human workers or robots. A resource, for instance a service robot, may be allocated on a task according to static or dynamic factors. Static factors refer to (1) whether a robot possesses the necessary capabilities to handle a task (e.g. an appropriate gripper or recognition system for a product), (2) whether the terrain is suited for the locomotion system of the robot and (3) whether the robot possesses the necessary software for performing the task. Dynamic factors of resource allocation deal with resources not always being readily available, as robots may be down for maintenance or otherwise engaged. The efficient and effective allocation of resources is paramount for automated and semi-automated processes in the intralogistics sector, where multiple processes run in parallel, while still sharing the same resources. Priorities of routine processes need to be set, as well as extraordinary processes need to be integrated in the decisional pipeline in order to be accomplished. To consider all these aspects at run-time, a process management technology must be able to handle the various requirements flexibly, while prioritizing resources according to specific constraints and adapting to new circumstances (Reichert, 2012).

2.1.2 Workflow

Processes control many of the high-level functions regarding intralogistics, such as decision-making; their explicit representation as process models is immensely beneficial, allowing for process optimization thanks to thorough analysis and subsequent removal of inefficiencies and inconsistencies. Ideally, these process models are also compatible with a process management system (PrMS), which becomes then capable at run-time of: (1) coordinating the flow of process information between all resources involved, (2) supporting users when executing processes by providing them with information and (3) communicating decisions to super and subordinated systems. Thanks to the modelling of processes and the use of a PrMS, the workflow can be flexibly

managed: process models can easily be changed and adapted to changing circumstances (Weber, 2008). These changes can be reflected in the actual process execution of future process instances or even in currently running processes: this often becomes necessary when there are long-running processes active at a given time as well as frequently updated regulations or possible process optimizations and changes. In such cases, running process instances must be updated flexibly at run-time to reflect the changes, a capability only few modern PrMSs provide (Künzle, 2011).

2.1.3 Tasks Execution

The software an autonomous robotic system consists of can be separated into different abstraction levels, among which the task abstraction level is one of the most abstract ones (RobMoSys, 2018). Modelling a task at symbolic abstraction level provides a representation of how the system parts of a robot are orchestrated to provide a service, such as the transportation of an item (Lutz, 2014). At the same time, the modelling of simple tasks (e.g. picking or transportation) allows for flexible composition of more complex tasks (e.g. picking and transportation, hence commissioning). In a design phase, tasks as building blocks are the foundation to offer and deliver services to a super-ordinated system and provide the link between processes and functionality. The composability of those tasks is an important prerequisite for the development of domain specific tools e.g. enabling a human operator to flexibly use an assisting robot, by adopting an existing task or by modelling a new one. In a run-time phase, the flexible execution of the tasks is a prerequisite for robust real-world capable robotics systems working in open and human-shared environments, where changes in the environment and unforeseen events need to be considered (Steck, 2011).

2.1.4 Human-Robot Interaction

Humans play always a fundamental role in automation, either as supervisors of an automated SoS or as active parts of the system itself, especially for the execution of those sub-tasks, which are particularly complicated to automate or for which accountability is required. The human-robot interaction belongs to the process flexibility because, depending on the complexity of the task, on the required performance, on the available resources and even on the time of the day, different resources (human or automation) might be allocated to different sub-tasks to seek an overall better efficiency.

2.2 System Flexibility

The dimension of system flexibility concerns the capability of a SoS of adapting itself or being adapted to achieve different goals, identified in the summarized sub-categories.

2.2.1 Applicability to Different Scenarios

The applicability of the system to different scenarios measures the capability of the system to fulfill requirements for a wider range of processes or domains, so that it can be successfully installed "out of the box" in different applications. Considering requirements from different scenarios, key to a wider applicability, generates however higher system development costs, which can be justified only in case of a real consequent increase in sales. In the development phase the selection of scenarios to be considered should be limited to those requirements, which bring a positive balance between increased development costs and potential increase in sales.

2.2.2 Adaptability after Installation

The adaptability measures the ability of a system to respond to certain unexpected changes after its installation without being completely reengineered. This is a fundamental characteristic in the dynamically changing environment of intralogistics, where specific tasks can change over a relatively short period and facility layouts need to be adaptable to the changing business. A scarce system adaptability to new slightly different requirements would prevent the possibility of spreading investment costs over a long time period, representing thus a barrier to the investment.

2.2.3 Integration with Installed Technologies

Integration with technologies pre-installed at the customer's site represent often the highest cost and therefore the greatest barrier to the market. To tackle this problem through integrational flexibility, a SoS should consider a variety of common integration requirements concerning material and information flow. This is done by (1) organizing the suitable interfaces to make the integration process as plug-and-play as possible and by (2) designing the system with a modular approach (see section 3), so that technological modules can be plugged or unplugged in favor of a smoother integration.

2.2.4 Scalability

The scalability measures the capability of an intra-

logistic system of increasing (or decreasing) its maximum capacity in respect to the demanded throughput, by adding (or subtracting) other instances of the system itself or sub-modules of it (Wencai, 2012). Designing a system in order to be up scalable (or down scalable) reduces the risk of investing in automation technology, by extending its service life, which would be otherwise short due to the constantly changing nature of the logistic sector. This degree of flexibility is particularly necessary for instance in the ramp-up phase of a hub for distribution, or for third part logistic providers, which continuously renegotiate the volume of their business.

2.2.5 Productivity

The concept of productivity is close to the one of scalability in respect to the capability of an intralogistic system of increasing (or decreasing) its throughput in respect to the demand. The difference is however, that for this sub-category, such degree of flexibility is reached without adding (or subtracting) other instances of the system itself, but just by controlling the output of the installed system. The flexibility reached through productivity adjustments of existing equipment is therefore limited in respect to the one that can be reach by up or downscaling the whole system. Productivity adjustments are particularly important in those systems subjected to seasonal fluctuation, such as the online retailing business in periods before e.g. Christmas or the by now global phenomenon of Cyber Monday.

2.2.6 Variants and Configurability

The ultimate level of system flexibility is the total modular configurability, where functionalities could be added or subtracted to the system by simply plugging and unplugging technological modules. Such total configurability could probably work in a software environment, but it is hard to achieve from a hardware standpoint, without an exponential increase of development costs. A halfway compromise between total configurability and a fix design is the creation of variants for a SoS: this means limiting the spectrum of technological hardware and software module that can flow into a system to a pre-defined set of configurations, each of which can be optimized for a specific set of functionalities. The design is nevertheless flexible, as to the possibility of integrating in a single SoS a set of different and alternative technological modules, but unlike the total configurability, the variant approach allows for containment of development costs.

2.3 Technological Flexibility

The dimension of technical flexibility concerns the intrinsic flexibility of technological modules composing the SoS.

2.3.1 Heterogeneity of Handled Goods

Handling and transport are the two processes that set the bases for intralogistics. On the lowest level, the basic aspect of flexibility at play is therefore the capability of a system to handle and transport heterogeneous goods. Heterogeneity can be due to mainly three factors: (1) physical, (2) informational and (3) environmental factors. Example of (1) physical factors of the items are dimensions, weight, shape (fixed or variable), surface (smooth, porous or damaged), and resistance (robust or fragile) (Bonini, 2012). Among the (2) informational factors the most relevant are the position of labels, and the means of the information (one- or two-dimensional barcodes, handwritten label, RF-ID etc..). For the (3) environmental conditions, heterogeneity is not an intrinsic characteristic of the goods, but rather depending on the way items are grouped or sorted. Increasing the flexibility of technological modules such as grippers, object recognition technologies and kinematics would result in the possibility of handling a wider range of heterogeneous items, thus favoring the applicability of the SoS.

2.3.2 Technological Capabilities

Technological modules composing a SoS embed functionalities, which are necessary to give the robot the capabilities to accomplish a task. The flexible composition of technological capabilities is paramount for the creation of a SoS through modular approach. Software models and model driven software development provides the tools to explicate those structures required to enable the flexible composition of software components, allowing the reuse of closed software components on model level. Robotic business ecosystems (RobMoSys, 2018) (SeRoNet, 2018) using those structures are currently being promoted and implemented, in which participants are able to exploit synergies and share risks, by offering their own software components to other participant, thereby gaining access to components offered by others. The developer of a robotic commissioning system, for example, can use the building blocks (thereby the expertise) of a robotics navigation expert and other building blocks to compose the system. The SmartMDSD-Toolchain (Stampfer, 2016) as an integrated development

environment makes those structures accessible to the participants of the ecosystem. Models, as machine readable representations for building blocks and their encapsulated functionality, allow for the explication of variation points within the building blocks. Those variation points can be used to enable flexibility to adapt the building blocks during system composition and system operation.

3 METHOD

In this section a new method for flexible modular configuration and evaluation of systems of systems is introduced, which, starting from process requirements and considering factors such as feasibility, development costs, market potential and effective impact on the current processes, enables the evaluation of a flexible SoS equipped with the needed functionalities before its actual development. The presented method is made of five major steps and takes in input requirements of potential users, technological modules implementing different functionalities (see first level of flexibilisation in section 2) and different system evaluation methods. The output of this novel method is a virtually configured SoS, with its documented evaluation. Some steps of the method can be re-iterated, either relaxing process requirements or re-arranging

technological modules, in order to find the configuration providing the best system evaluation. Each iteration yields a documented evaluation of the configured system, hence providing not only a decisional support tool for the design, but also a tool for the tracking and documentation of these decisions. This section is set to explain the five steps of the method; in the next section an example is reported.

3.1 Collection of User Stories

User stories serve the purpose of collecting a critical mass of potential user, which have the wish for automation of the same (or similar) intralogistic processes, but in potentially very different domains, branches and applications. The potential users have in common the need (or wish) for automation and the lack of suitable (as in effective and efficient) systems on the market.

3.2 Translation into Requirements

The translation of user stories into requirements is fundamental to identify the needed functionalities, with a particular focus on the type of needed flexibility (process, system or technological – see section 2). In the first iteration of the method, requirements should be comprehensive of all possible different application of the system under design, because this would allow for a wider adoption after the realization. As the next steps of the method are implemented, considering a wide variety of requirements, thus adding more functionalities to the system, could result either impossible or inconvenient (discovered during step 4 - system evaluation).

As the method progresses, or in following iterations of the method, some of the requirement might be sorted out, thus leaving behind some of the potential users, which will reduce the critical mass, needed for spreading the development costs.

3.3 System Configuration

Thanks to the collection of requirements and the identification of necessary functionalities in the previous step, the system can be virtually configured with a modular approach drawing technological modules from a pool of existing technologies, each contributing to different system abilities. Example of these technologies are the following macro categories: object recognition, navigation, grasping, transportation, booking (in connection with a warehouse management system - WMS), decision-making, mission planning, collision avoidance, robot
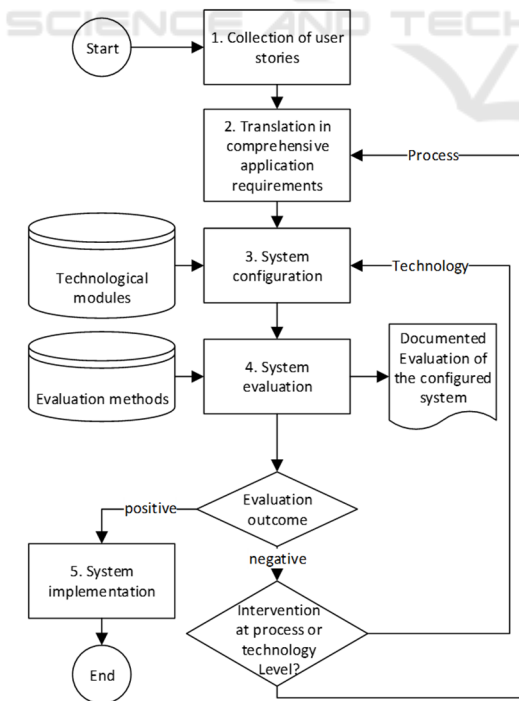

Figure 1: method for flexible configuration of Sos.

kinematics etc. Each of these macro-categories can be divided into technological sub-modules that can implement very different functionalities.

3.4 System Evaluation

In this step, the virtually configured system is evaluated against general and application-specific criteria. First (4.1) feasibility and (4.2) development effort are evaluated according to general criteria. The goal of the (4.1) feasibility evaluation is to assess whether the integration of different technology modules is possible and to give a numerical evidence of technical boundaries of the new virtually configured system. Once feasibility has been positively assessed, the (4.2) development effort has to be determined: here both the procurement costs (hardware and software) and the integration costs need to be considered, together with an estimated effort for fine tuning in order to reach the target performances of the system.

The next step of the analysis is the evaluation of application-specific criteria. Here first and foremost the (4.3) market potential needs to be estimated for each application, domain and branch considered in step 1 of the method (Urru, 2015). This assessment, together with the estimated (4.2) development costs, can give the system developer a first insight on the potential of realization of the virtually configured SoS. Another application-specific criterion to evaluate is the performance of the system in the single application calculated in comparison with the existing process (manual or semi-automatic): this yields an application-specific (4.4) assessment of the advantages (savings, increased capacity, increased ergonomics etc.) of the system with respect to the current process (Urru, 2017). In case of negative evaluation of any of the four criteria, the method might loop back to previous. This can happen in any of the following cases: if the system is (4.1) not feasible, if the (4.2) development costs do not match the (4.3) market potential or if the (4.4) advantages on the current process are not satisfactory. In these cases another configuration of the system could be proposed (back to step 3 of the method – system configuration), or a simplification (relaxation) of the requirements for the system could occur (back to step 2 of the method – translation into requirements). In this second case, as some of the functionalities are sorted out and not implemented in the system, potential user could be left behind and this needs to be coherently considered in the estimation of the market potential.

In case of positive result of the evaluation, after one or more iteration of the method, the system implementation (step 5) can begin.

4 METHOD APPLICATION

In this section, a simplified example of application of the method is described: the first step is the collection of user stories (step 1). In this simplified example, the focus is set on the processes of commissioning and replenishment (complementary and symmetric to commissioning) of items in a warehouse. The first user story comes from the pharmaceutical sector and targets the process of product returns: these products are checked for quality and expiration date upon arrival and, overnight, replenished back into the shelves of the warehouses. Since normally only specific products with low turnover are returned, the required performance is not high, but the process is rather inconvenient (additional night shift with labor involved), hence the wish for automation. The second user story comes from the sector of internet retailing and focusses on the process of commissioning in a warehouse: the shape of the stored items can vary from rigid cuboid, to flexible sack- or bag-shaped and the weight can range from 0.1Kg to 20Kg. A high performance is in this case critical to the success of the automation, as the company seeks an increased picking capacity. The third user story comes from the food retailing sector and the process in question is the replenishment of shelves for packaged food in a supermarket. Since the replenishment needs to happen during opening time of the shop, particularly important is the safe interaction of the automation with the customer. Items can vary from very fragile glass bottles of wine, to fresh mozzarella bags and weights can range from 0.05Kg to 5Kg.

The second step (step 2) of the method is the translation of all user stories into comprehensive requirements, inclusive of all collected scenarios. This enables the identification of required functionalities, such as an Optical Character Recognition (OCR) reading module for the proof of the expiration date in the pharmaceutical (first user story) and food retailing sector (third user story).

Once the needed functionalities are listed, thanks to the database of available technology modules, the first virtual configuration of the system can start (step 3). A digression concerning the database of technology modules is at this point necessary. In order to keep the database up to date, explicit or implicit collection of user stories from the point of view of technology providers should be collected. For

the simplified example reported in this section, it is assumed that the database can be filled with the following technological modules provided by different technology producers and developed for other niche applications: (1) an OCR developed for the postal sector to read hand-written addresses, (2) a mobile platform equipped with navigation modules and a manipulator for the feeding of small cylindrical parts (0.01Kg to 5Kg) to a production line by means of a two-finger gripper, (3) an object recognition module for cuboid-shaped goods, (4) an object recognition module for bags and sack-shaped goods, (5) a barcode reading module connected to a WMS and (6) a suction cup gripper suited for small non-porous items up to 5Kg. If the configurator of the system is experienced and well aware of the technological state of the art, the configuration (step 3) happens together with a preliminary feasibility study (step 4.1). The preliminary feasibility concerns mainly hardware integration aspects, such as respect of payloads, energy demands, and constructional mechanical stress. This helps filtering out some system configurations that are clearly not feasible, such as mounting a gripper on a manipulator with a payload lower than the gripper itself. In order to remain inclusive of all functionalities needed by the different users in the example, the mobile platform equipped with the manipulator should be strengthened to support items up to 20Kg, it should be equipped with the OCR, the barcode-reading and cuboid-shaped object recognition modules and the whole system should be integrate with a WMS.

The proposed configuration, yielded after the first iteration of the method, is then evaluated (step 4). Assuming that (4.1) this configuration is technically feasible and (4.2) that the development effort is justified by (4.3) the potential market in the three sectors, the (4.4) advantages of application of this configuration are then evaluated in each sector. In this step of the evaluation (step 4.4) the following complications emerge: (1) the mobile platform, strengthened to reach the 20Kg requirement of the second user story, is not applicable in a supermarket (third user story), both because of layout problems and because of safety regulations; (2) the system does not deliver improved overall performances in the commissioning (second user story); (3) in order to handle the variety of goods in the supermarket two different interchangeable gripper are necessary (a two finger-gripper and a suction cup gripper); (4) in the pharmaceutical (only cuboid goods) and the internet retailing sector (only non-porous items) the most performing way to grasp items is through a suction cup gripper. Considering this technological remarks,

provided by the evaluation step, the method can be re-iterated in order to obtain a system configuration that can be positively evaluated.

It is evident that the second user story (internet retailing) poses challenging requirements, with high impact on the negative result of the evaluation. Only after acknowledging the lacks of the new configured system, especially concerning performances, the method loops back to its second step (step 2), where requirements are analyzed again and alternately relaxed, seeking synergies towards a partial automation of a slightly modified process. In this specific user story of internet retail, it would be for instance possible, to divide the warehouse in four areas according to item size and required picking performance. The commissioning of small items requiring high picking performance (fast movers) could be achieved through standard technologies such as the Autostore or the Amazon Kiva system; the commissioning of large fast movers could be automated with an automatic storage and retrieval technology; the commissioning of large slow movers (low picking performance required) could remain manual. The last part of the warehouse, namely the one dedicated to the commissioning of small (up to 5Kg) slow movers could be automated through a small mobile platform, which could be suitable for the automation of the other user stories as well.

The system is therefore re-configured (step 3) in order to fulfill the new (relaxed) requirements. As the necessary payload is reduced to 5Kg and performances are not the highest priority for the system, the existing mobile platform equipped with the manipulator can be used, equipped with the OCR, barcode-reading and cuboid-shaped object recognition modules and with an interchangeable gripper (two-finger and suction cup). An interface to the central WMS completes the system configuration, result of the second iteration of the method.

The relaxation of requirements has two different and opposite effects highlighted by the evaluation of the new configuration (step 4). On the one hand, the development costs sunk, as the platform does not need to be strengthened to reach the 20 Kg requirement, but, on the other hand, the market potential shrunk, as only approximately 25% of the processes in the second user stories can be automated with the proposed technology. If, considering the significant reduction of development costs, the market potential is still appealing, the system is evaluated in each scenario for its efficiency (saving, performances etc…). If this final part of the evaluation is positively concluded, the obtained results can be also used as a marketing tool to ease the

decision to invest. Once a commitment of some sort has been stipulated with potential users (for instance those providing the initial user stories) the implementation of the system can begin.

5 DISCUSSION

The weakest link of the proposed method resides in the fourth step: the system evaluation. This is not due to the difficulty of the evaluation itself: in literature several methods for assessment of (4.1) feasibility, (4.2) development costs, (4.3) market potential and (4.4) performance and economic advantages of automation can be found, which could be applicable. The evaluation is the weakest link of the method because what is being evaluated is not an existing SoS, but a virtual one, configured in step 3 (system configuration) on the bases of the required functionalities. The power of the evaluation resides in its numerical and possibly objective aspect, but if the system under evaluation is 100% virtual, one could argue that this numerical quantification becomes vain, invalidated by the too many necessary assumptions. However, the configured SoS will normally consist in great majority of an existing platform (in the example, the mobile platform with navigation modules and manipulator), which needs to be modified by adding some other technological modules. The existing technological platform will account for a consistent percentage of the whole system, so that the remaining share, upon which assumptions need to be made for the evaluation, will have a relatively minor impact in the uncertainty of realization. Although this does not fully erase the risk of evaluating a partially virtual system upon some assumptions, this risk is mitigated by reducing the impact of such assumptions, hence restoring the value of a quantitative evaluation.

Future research will focus on the validation of the proposed method through at least three different applications, for different intralogistic processes.

6 CONCLUSION

After a brief introduction on robotics in intralogistics, in this paper an alternative taxonomy of flexibility was introduced together with a novel method for flexible modular configuration of systems of systems. The novelty of the method relies in the possibility of evaluating the virtual systems of systems, equipped with the needed functionalities, before its actual

development. This is accomplished first analyzing all process requirements, then assessing factors such as feasibility, development costs, market potential and effective impact on the current processes. Thanks to the evaluation before realization, the development effort is focussed on those aspects of flexibility that add market value to the system, thus promoting the efficient development of systems addressed to interested customers in intralogistics. An example of the method application was given and the main outcomes discussed.

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