Lean Human-Robot Interaction Design for the Material Supply Process

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Abstract: Powered by e-commerce and vital in the manufacturing industry, intralogistics became an increasingly important and labour-intensive process. In highly standardized automation-friendly environments, such as the automotive sector, most of efficiently automatable intralogistics tasks have already been automated. Due to aging population in EU and ergonomic regulations, the urge to automate intralogistics tasks became consistent also where product and process standardization is lower. That is the case of the production line or cell material supply process, where an increasing number of product variants and individually customized products combined with the necessary ability of reacting to changes in market conditions led to smaller and more frequent replenishment to the points of use in the production plant and to the chaotic addition of production cells in shop floor layout. This led in turn to inevitable traffic growth with unforeseeable related delays and increased level of safety threats and accidents. In this paper, we use the structured approach of the Quality Interaction Function Deployment to analyse the process of supply of assembly lines, seeking the most efficient combination of automation and manual labour, satisfying all stakeholders´ requirements. Results are presented and discussed.

1 INTRODUCTION

In 2017, the highest robot density (that is the number of multipurpose industrial robots in operation per 10.000 persons employed) was measured in the automotive industry accounting for the 33% of worldwide robot demand: in Germany, for instance, 1.162 units were installed per 10.000 automotive employees, in the Republic of Korea 2.435 units. When considering only general manufacturing industry (manufacturing excluding automotive), the numbers of units go down to 191 in Germany and 533 in Republic of Korea. The weighted average robot density of all manufacturing industry (general plus automotive) was assessed at 322 units in Germany and 710 in Republic of Korea (IFR, 2018).

The high robot density in the automotive sector is related to the high level of product and process standardization, result of an effort accomplished in decades in this sector, in order to reach highest throughput and quality with minimum costs. In such automation-friendly environments, the cost-benefit ratio of using robotics (Bonini et al., 2015) is positive, because of three conjoined effects: (1) increase of throughput (capacity), (2) decrease of costs, and (3) improvement of product quality.

With the decreasing of the standardization level of products and processes, becomes harder to achieve a positive impact on capacity, costs and quality (Bonini et al., 2018). Complex tasks in less standardized environment require robot technologies that, when existing, are more expensive and less performing, increasing the barrier to invest (Bonini et al., 2015). This happens often in the general (non-automotive) manufacturing sector, characterized by dynamic production processes, regulated by demanding requirements of a fast-paced global economy.

Especially the automation of the intralogistics activities in the general manufacturing and automotive supplier sector became challenging. Increasing number of product variants and individually customized products combined with the necessary ability of reacting to changes in market conditions led to smaller and more frequent replenishment to the points of use in the production plant and to the chaotic addition of production cells in shop floor layout (Urru, Bonini and Echelmeyer, 2018). This led in turn to inevitable traffic growth with unforeseeable related delays and increased level of safety threats and accidents. These risks made the logistic systems and thus the whole production process vulnerable to inefficiency such as information

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loss, loss of control in the work-in-process level, redundant inventory stored as buffer at the point of use in the plant, missing parts, wrong parts delivered and excessive inventories (Harris, Harris and Wilson, 2003). In logistics, the achievement of a higher robot density has at least one additional relevance argument and one additional criticality. The first is a demographic component: in industrialized countries, where quality of life is relatively high, unemployment rate is low and population is ageing, it is becoming increasingly hard to find labour willing to take over ergonomically hard jobs (Abeliansky and Prettner, 2017). The second one is the impossibility of the customer to perceive any improvement in quality due to automation. These two argument make it at the same time more challenging and more necessary to increase the robot density in logistics, which is a challenge that especially online wholesalers take really seriously. Amazon for instance issues every year since 2015 the "Amazon picking challenge" (Correll *et al.*, 2018) to stay close to the best basic-research development in object recognition and grasping for small items of different nature (Morrison *et al.*, 2018). At the same time, Amazon deployed the KIVA system on a large scale in its distribution centres and warehouses. This automates the transport functionality of the commissioning process using high performance available technology, while leaving the unstructured task of the picking to a human operator (Li, 2016).

Recent research (Bonini and Echelmeyer, 2018; Bonini, Urru and Echelmeyer, 2019) focuses on formalizing this empirical process of finding the right level of automation. Answering in a structured way to the question "who-does-what" between man and automation could be the key leading to lean human-robot interaction, thus increasing the robot density even in the logistic sector, with a substantial relief for human operators of ergonomically hard tasks. Using the structured approach provided by Bonini et al. (Bonini, Urru and Echelmeyer, 2019), in this paper we analyse the process of supply of assembly lines, seeking the most efficient combination of automation and manual labour, satisfying all stakeholders´ requirements. After a brief summary of the state of the art for allocation of functionalities between human and automation, with a specific focus on the Quality Interaction Function Deployment (QIFD) method for lean HRI, we present the scenario and the result of the application the QIFD, which are then discussed.

2 STATE OF THE ART

As fully autonomous systems are often too expensive and low performing and simpler cheaper systems are not enough flexible, Bonini et al. (Bonini, Urru and Echelmeyer, 2019) proposed to set the focus on using simpler cheaper systems in interaction with human operators. If the interaction is well designed, this could improve costs, performances and acceptance. In order to find convenient balance between manual work and automation solutions, first the so-called "all-or-non-fallacy", namely the false idea that either a process should be fully automated, or it should be fully manual (Sheridan and Verplank, 1978), needs to be abandoned. This presumes an allocation of functions among automated and human agents that can follow several principles, the simplest of which is the Fitts´ list "Men are better at-Machines are better at" (MABA-MABA) (Fitts, 1951) updated through the years as new technologies were released (Price, 1985; Hancock and Scallen, 1998). More elaborated qualitative and quantitative approaches are those of the comparative, leftovers and economic allocation (Rouse, 1991) or the sharing of control (Inagaki, 2003). Most of these methods approach heuristically the function allocation problem, delivering results that need to be validated. Others (Ranz, Hummel and Sihn, 2017) developed analytic approaches aimed to objectivize the function allocation problem by seeking an optimal solution. While effective for a narrow and specific low-level task of the work breakdown structure, these kind of analytic optimum-seeking approaches are ill suited for the analysis of a large process chain, where too many dynamic parameters come at play. The problem with existing methods from the literature is that they are either exclusively qualitative, or, in the effort to quantify the decision making process, focus on a narrow array of parameters. For this reason, with the objective of function allocation in the line supply process, in this paper we use the alternative approach introduced in (Bonini and Echelmeyer, 2018) and refined in (Bonini, Urru and Echelmeyer, 2019), namely a 12-steps heuristic method that functions as a decisional support for process design. The method has been applied in a focus group, where participants had various competences. The decisional process has been tracked and documented using the House of Quality Interaction visual tool. Thanks to the QIFD method, different automation scenarios were created and evaluated with respect to their compliancy to two sets of requirements of all process stakeholders: (1) hard requirements, representing the view of the investors and considering parameters such as the need for automation, efficiency and performance and (2) soft requirements, representing the view of the user/partner of the automation, thus considering parameters such as ergonomics, complexity, work balance, accountability and acceptance. The 12 steps of the method are in order: (1) eliciting and weighting of hard requirements, (2) identification of needed functionalities, (3) evaluation of impact of functionalities on compliancy to requirements, (4) identification of synergies and conflicts in automation of functionalities, (5) calculation of utility of functionalities, (6) estimation of relative complexity of automation and relative complexity of manual execution of each functionality, (7) calculation of convenience of automation for each functionality, (8) creation of automation scenarios based on convenience and synergies or conflicts, (9) estimation of compliancy of each scenario to hard requirements, (10) estimation of relation between functionalities and the perception-action model (Parasuraman, Sheridan and Wickens, 2000), (11) calculation of compliancy of each scenario to soft requirements, such as complexity of automation, ergonomics, workload balance (mental and physical), accountability and acceptance, (12) calculation of total requirement compliancy score from compliancy to soft and hardware requirements (Bonini, Urru and Echelmeyer, 2019). The application of this method (section 4) to the scenario described in section 3 lead to novel results, namely to an innovative human-robot interaction approach for the material supply process, presented in section 5 and discussed in section 6.

3 SCENARIO DESCRIPTION

Being the scope of the investigation the material supply process in a generic production plant, in this section, a typical scenario is introduced. As illustrated in Figure 1, the transportation of material in production logistics takes place between 4 main areas: (1) warehouse, (2) supermarket (SM) work cell or station (WS) and (4) outbound. After the inbound process different kinds of unit load (UL), such as for example coils, boxes, mesh cages and pallets, are stored in the warehouse. From the warehouse, the goods are then transported to the supermarket where they are prepared to be delivered to the work cell Usually, in this phase, the goods are bundled in standardized unit loads according to the company best practice. The selectivity in the supermarket is often high, meaning that the unit load, which contains homogenous goods, could be individually handled. According to the needs, in unit load, of each work cell, a transportation order list is compiled. The unit loads are commissioned in the super market and transported to the related work cell. Once the material has been utilized, the empty unit load (i.e. euro container) needs to be transported back to the SM, so that the cycle could start again. For the sake of completeness, in Figure 1 also transportation of work in progress (WIP) between work cells and of the final products to the outbound area are represented.

The analysis focuses both information and material flow between supermarket and work cell. Moreover, to simplify the method implementation, we will consider a scenario where the supermarket is dedicated to only one unit load: euro container. The full euro containers are commissioned in the supermarket and transported to the workstation by means of manual transport/push carts or forklifts. The transport cart is pushed to the nearest reachable area (H), where the euro container is actually needed, the point of use (PoU), as shown in Figure 2. Once the area H is reached, the operator manually picks the full euro container and transports it to the PoU. As the full euro container is positioned in the shelf, the empty one could be brought back to the push cart. This process is repeated until all the euro containers on the push cart are delivered. The empty euro containers collected during the delivery tour are then brought back to the SM and the commissioning process into the SM starts again.

On the basis of this scenario, in the next section, the design of a lean Human-Robot Interaction for the material supply process will be presented.

4 METHOD APPLICATION

In this section, for each step of the Quality Interaction Function Deployment presented in the state of the art, a brief description of the main results will be given.

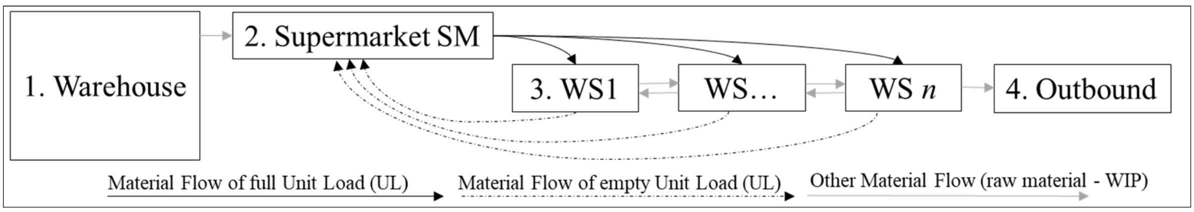

Figure 1: Example of material flow in production logistics.

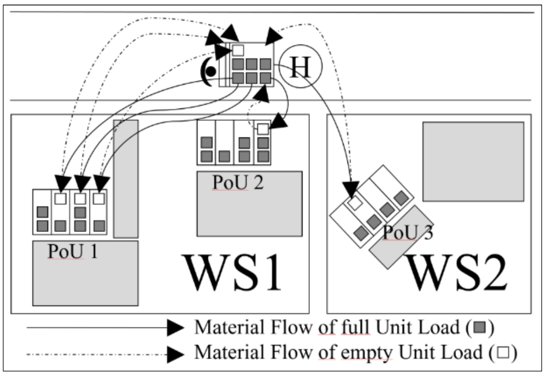

Figure 2: Material flow between H and PoU.

For the sake of conciseness, some steps of the QIFD method are here reported as grouped (e.g. 4.3 Impact, Correlation and Utility).

4.1 Hard Requirements

In this first step of the heuristic method, hard process requirements are investigated. Given the dynamicity of a modern production process, as already mentioned in the introduction, and the general goal improving the processes through automation, a list of 13 requirements has been identified. The requirements have been then analyzed and ordered by importance. To avoid influencing the final result with personal opinions and believes on automation priorities, the same weight has been assigned to all the requirements concerning automation.

The resulting requirements ranking with the related normalized importance (in brackets) follows: (1) the system must efficiently answer throughput changes (0,11), (2) the system must be able to efficiently answer to changes in the layout (0,10), (3) the system must generate a low traffic (0,10), (4) the system must be scalable (0,09), (5) the system must be able to handle different kind of standard UL (0,08), (6) the ordering of full UL (0,06), (7) the commissioning of full UL in the SM (0,06), (8) the preloading of full UL (0,06), (9) the loading of full UL (0,06), (10) the transport of UL between Supermarket and H (0,06) (11) the transport of UL between H and PoU (0,06) (12) the exchange full-empty UL (0,06) and (13) the unloading of empty UL (0,06), must be automated.

4.2 Functionalities

After eliciting the requirements, functionalities are to be deployed and divided to the atomic level in which they could be assigned to either the human or the automation. The list of identified functionalities is hereafter given: (1) ordering of full UL, (2) commissioning of full UL, (3) preloading of full UL, (4) loading of full UL, (5) transport of UL between SM and different H, (6) navigation between SM and different H, (7) transport of UL between H and PoU, (8) navigation between H and PoU, (9) exchange full/empty UL at the PoU, (10) Unloading of empty UL.

4.3 Impact, Correlation and Utility

Once the impact of hard requirements on each functionality has been assessed by means of a logarithmic scale and the correlation between automation of different functionalities have been evaluated, the relative utility of each functionality have been calculated. The functionalities with the highest utility are: 1) ordering of full UL, 2) commissioning of full UL, 3) preloading of full UL. While the functionality with the lower utility is the transport of UL between SM and different H.

4.4 Complexity

In this step the complexity is evaluated from two different point of view: 1) the complexity of automation and 2) the relative complexity the human operator encounters in the manual execution of a functionality. For instance the most complex functionality to be automated turns out to be the exchange full/empty UL at the PoU, while the most complex and strenuous functionality, currently manually executed by the operator, appears to be the commissioning of full UL.

4.5 Convenience

Estimating the convenience considers both the potential benefits of automating high impact functionalities, even if their automation has a high complexity level, and the possibility of automating low impact functionalities, when their automation is extremely simple (low complexity). The functionalities are ranked according to their convenience. This ranking will be input for the next step of scenarios development. The most convenient functionalities to be automated are: 1) ordering of full UL, 2) commissioning of full UL and 3) the transport of UL between SM and different H.

4.6 Scenarios

Overall 12 different scenarios are identified. Starting from a fully manual scenario, functionalities have been assigned to automation according to the convenience and the correlation matrix. For each scenario automated and manual processes are described together with the needed technologies.

4.7 Compliancy Hard and Soft Requirements

In the following method step scenarios are evaluated against hard and soft requirements. The hard requirements are the ones identified in the beginning, while the soft ones encompass (1) complexity of scenario automation, (2) ergonomics, (3) mental work balance, (4) physical work balance, (5) accountability and (6) acceptance. To each scenario a weighted score is assigned. Scenarios are ordered in a ranking according to the score. In the following section, the first three scenarios of the ranking will be presented.

5 RESULTS

The top tier scenarios will be hereafter described considering three main aspects: (1) functionalities allocation, (2) technologies and (3) processes.

In Table 2 functionalities are assigned according to the scenario to the worker (M - manual) or to the automated solution (A - automation). As noticeable in Table 2, some of the functionalities are either manual or automated, independent of the scenario (greyed out rows).

For each functionality to be automated, the appropriate technology should be chosen. A summary of the technologies chosen is introduced in the following Table 1. The logistic system concept for the material supply is based on tugger trains. Thanks to the information system and sensors available at the POU, the material is directly ordered at the POU and the picking list automatically compiled. The picking

Table 1: Functionalities and technologies.

	Functionality		Technology
1	Ordering of full UL	A	Direct order, information system and sensors at the POU
2	Commissioning of full UL	A	Aautomated Storage and Retrieval System or similar
3	Preloading of full UL	A	Drive-Thru Loading Concept
4	Loading of full UL	A	
5	Trasnport of UL between stations	A	Tugger Train
7	Trasnport of UL between station and POU	A	Mobile platform (AGV)
10	Unloading of empty UL	A	Drive-Thru Loading Concept

Table 2: Scenarios and functionalities allocation.

	Functionality	Scenario 1	Scenario 2	Scenario 3
1	Ordering of full UL	A	A	A
2	Commissioning of full UL	A	A	A
3	Preloading of full UL	A	A	A
4	Loading of full UL	A	M	M
5	Trasnport of UL between stations	A	A	A
6	Navigation between stations	M	M	M
7	Trasnport of UL between station and POU	A	M	A
8	Navigation between station and POU	M	M	M
9	Exchange full/empty UL	M	M	M
10	Unloading of empty UL	A	M	A

list is fed to an automated storage and retrieval system (AS/RS), which will take over the commissioning process of the needed ULs. The UL will be then automatically sorted and prepared for the loading on the tugger train by means of a Driving-Thru loading concept, developed by the Technische Universität München (Dewitz, Galka and Günthner, 2012). The automatic loading is only foreseen for the scenario1. In scenario 2 and 3 the loading of the full UL is done manually. The functionality of transport of UL between stations is always accomplished by means of a tugger train, driven by an operator. Once the tugger train has reached the target station H, the UL should be transported to the POU as shown in Figure 2. An additional trailer should be considered, in order to transport a mobile platform, which is able to carry more than one UL at a time and to follow the operator up to the POU. At the POU the operator will exchange the full UL with the empty one, then the mobile platform (AGV) will follow the operator back to the tugger train. After delivering all the UL, the operator drives back to the SM where in the case of automated functionality (scenario 1 and 3) the unloading of empty UL could be accomplished by the same technology Driving-Thru loading concept. The tugger train is ready to start a new delivery cycle. In Figure 3 the scenario 1 is graphically described. Comparing this scenario with the initial fully manual one, it is noticeable how the number of transportation needed

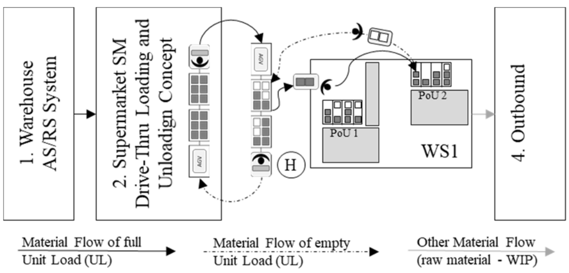

Figure 3: Lean Human-Robot Interaction concept for the material supply process.

to fulfil the overall material need is drastically decreased. Mainly thanks to the advantages offered by the two transportation technology chosen: the tugger train and the mobile platform (AGV). the introduction of an AGV able to carry more than one full UL at a time reduces the empty travel, increasing the overall system efficiency.

6 DISCUSSION

The top tier scenario of the 12 developed logistic concepts are in this section briefly discussed.

The most promising scenario, scenario 1, is the best in ergonomics due to the automation of loading of full UL, of the transportation between station H and PoU and of the unloading of empty UL. The acceptance of the scenario ranks also as the best, thanks to the active involvement of the operator. Technologies available for the implementation of this scenario will be ripe enough to be integrated in a whole system with a short-term horizon (within about three years). Development effort to adapt the AGV platform is estimated to be low.

The second ranked scenario, scenario 2, could be implemented without any development effort, since the loading of full UL, the unloading of empty UL and the transportation of UL between station H and PoU is manual. Within this scenario, only the most impacting processes are object of automation, i.e. the processes of ordering, commissioning, pre-loading process and that of physical transportation from the SM to the stops of the route H (but not the process of navigation).

The third ranked scenario, scenario 3, differs from the previous one only in two aspects. The transport of UL between H and PoU, manual in scenario 2, is now automated as is the unloading of empty UL, manual in scenario 2. With respect to scenario 1, the loading of full UL is here manual instead of automated; this creates a disadvantage concerning ergonomics, but an advantage concerning the smaller impact on exiting layout making it overall a less investment-intensive logistic concept.

It is important to remind that these results were achieved using a heuristic method and should not be considered as optimal, but rather as the best achievable result of the competences and discussion of the participants to the focus group. This means that different participant with different background and knowledge could have, for instance, chosen different technologies. Moreover, different focus groups and different application contexts could lead to a different interpretation of hard and/or soft requirements, with a non-negligible impact on their ranking/weighting process. This could lead to substantially different logistic concepts, compared with the ones presented in this paper. For these reasons, in the forthcoming research, results should be validated with an economic convenience analysis. The analysis should aim at estimating and assessing the economic effort to implement each different logistic concept, providing an additional criteria for the overall concept evaluation.

7 CONCLUSION

After the explanation of the relevance of the topic and an overview on the state of the art in function allocations among automated and human agents, in this paper we used the structured approach of the Quality Interaction Function Deployment to analyse the process of material supply in production environments. Applying this method, we designed 12 automation scenarios that were evaluated and discussed with respect to their compliancy to two sets of requirements: (1) hard requirements, representing the view of the investors and considering parameters such as the need for automation, efficiency and performance and (2) soft requirements, representing the view of the user/partner of the automation, thus considering parameters such as ergonomics, complexity, work balance, accountability and acceptance. The three top tier of the 12 scenarios were presented and discussed. Considering the currently available technologies, the most promising logistic concept for the automation of the material supply process in production environments envisions a lean human-robot interaction with the automation of all activities, except the navigation and exchange of full/empty unit loads at the point of use, which are still being assigned to the human operator.

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