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Dynamic Resource Allocation Considering Ergonomics in Intralogistics

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***Abstract* - Reacting to ever-changing business environments, in the last decade complex systems of systems accomplished giant leaps forward leading to great technological flexibility. However, this dimension of flexibility is often limited by the rigidity of super-ordinated planning systems. Especially when hybrid teams of automated and human resources are in place, the dynamic assignment of tasks taking into account ergonomics remains a challenge. After exposing a gap in the state of the art on the topic, this paper presents an approach to include ergonomics in dynamic resource allocation models. Combining and complementing existing approaches, the presented method monitors the actual ergonomic burden of the resources during a shift and it provides a linear optimization model to steer the resource allocation process.**

Keywords – dynamic resource allocation, assignment problem, ergonomics, linear optimization model, logistics

I. Introduction

While global economic downturns and trade tensions left their marks in 2019, causing a plain drop of 12% in the global traditional robotic systems installations [1], the market of professional service robots showed a strong growth of 32%, in comparison to 2018. The strong demand for logistics robots, accountable for the 43% of the total service robots sales, has been fostered by the adoption of flexible robotic logistics solutions in warehouses, factories and for home delivery, sustained by the success of the “Robot as a Service” business model [1]. This trend confirms that, in order to keep being competitive in the current dynamic economic environment, companies have focused their efforts on improving production and logistic systems, enhancing their abilities of efficiently responding to unexpected events [2][3][4]. Especially in intralogistics scenarios, technological advancements combined with the constantly increasing need for flexibility [5], led to the development of complex, flexible and heterogeneous systems of systems, where service robots and operators coexist and cooperate, often coordinated by high-level business process management systems [6]. These systems, usually implemented where digitalization levels are adequate, are able to manage and execute different process alternatives and to coordinate a pool of different resources, providing the precondition to react to unexpected occurrences [7][8]. Under these circumstances, the same task could be effectively accomplished by employing different resources or different combinations of resources. Although the result of the main process (e.g. an assembled product) may not change, the choice of the team of resources allocated on the task may substantially influence some key performance indicators (KPIs), ultimately affecting the overall system efficiency. In these flexible and interactive environments the resource allocation problem, as part of the process flexibility dimension, described by Bonini et al. [9], becomes particularly relevant to maximize the benefits of adopting flexible systems of systems. Available resources should no longer be allocated according to static allocation logics, periodically updated, but should be dynamically assigned, during operations, according to their characteristics and availability [10], hence considering static and dynamic parameters, without losing sight of the company goal deployment plan [11]. Current decision models for centralized logistic systems could not fulfill these requirements, since they revolve around fixed control loops and static rules [12] [13]. According to these models, resources are allocated in advance on tasks based on forecasts, under strict observance of fixed assigned operational areas and transport paths [14] [15]. The application of such decisional models designed for traditional logistics systems to flexible systems of systems could lead to inefficiencies and thus offset the potential benefits offered by flexibility. Dynamic resource allocation models are therefore necessary to deal with the dynamicity of unconstrained logistic scenarios and allocate service robots, operators and potential teams of resources to the most fitting task, given a set of current circumstances. The trade-off among costs, flexibility and performance identified by Bonini et al. [16] could be consequently solved by allowing a smart collaboration between service robots and operators, fostering the further automation of logistics processes. As it might be expected, alongside with traditional parameters such as costs and performance, also ergonomics should be taken into account to steer the resource allocation process in dynamic environments. The main goal would be to avoid the deterioration of the quality of work for operators. Ergonomics plays a fundamental role in the design of logistic workplaces [17] and literature researches, surveys and case studies [18] provided evidence that ergonomics is considered by operators to be a one-dimensional quality attribute of logistic operations (according to the classification proposed by Kano) [19]. However, current dynamic resource allocation models do not sufficiently consider ergonomics.

The goal of this work is to address the identified research gap by designing an innovative approach to include ergonomics in dynamic resource allocation models. The aim is to assure fair working conditions even in dynamic logistic

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environments where flexible systems of systems are in place, thus increasing job quality and attractiveness without compromising the productivity.

After providing the reader with an overview of resource allocation models and ergonomics in intralogistics (chapter II), a novel method for monitoring the actual ergonomic burden of the resources during a shift and steering the resource allocation process is presented (chapter III). The proposed method is discussed (chapter IV) and an outlook on future research leads to the conclusions (chapter V).

II. Related Work

In this chapter, an overview of the state of the art is given focusing first the current dynamic resource allocation models (A), then on how ergonomics is perceived and measured in intralogistics scenarios (B).

A. *Dynamic resource allocation models*

The problem of resource allocation is a weighted, bipartite matching problem. According to a set of criteria, which usually encompasses cost and time, resources should be assigned to a list of tasks. Since the amount of tasks could be greater than the amount of resources, it is possible that more than one solution is admissible. This means that different scenarios could be generated, where a specific resource is allocated to a different set of tasks. The best scenario is then chosen with the aim of optimizing a given objective function or a set of key performance indicators [20][21]. The decision process of selecting the alternative with the greatest advantage should be guided by considering a defined target system and a set of given circumstances [22], which might continuously vary in dynamic environments. Since the target system is usually defined by deploying strategic goals into operational ones, the operational decision of resource allocation directly contributes to the achievement of the institutional goals [23]. Defining the target system has therefore a relevant impact on the resource allocation, no matter which method is employed to support the decision of which assignee should perform which task.

Especially in logistics, hierarchical target systems are widely recommended and two main goals are pursued: (1) increase of performance to fulfill process or customer requirements and (2) reduction of costs or increase in profitability [5][11][24];

Linear programming (LP) optimizations techniques have been successfully applied to solve the resource allocation problem, minimizing a total cost function [25][26]. Auction-based assignment models, populated by eager resources whose goals is to maximize their profit by hoarding convenient transport orders, have been proposed in [27] and [28]. Price-based decision models, which build upon the concept of *degree of achievement* of the optimization goals and allow, for instance, to include penalties in the optimization model for exceeded deadlines, costs for resource consumption and empty run distances, have been introduced in [29]. Criteria such as punctuality of delivery, transport duration, waiting time and process costs have been considered when designing resource allocation models based on Extended Profitability Appraisal (EPA) in [14].

Table I. Relevant criteria for resource allocation models

		Assignment problem of LP (expanded) [26][25]	Auction based assignment model [7][28]	Price-based decision model [29]	Extended Profitability Appraisal [14]
Criteria	Costs	Process costs	Costs define supply and demand value	Resource consumption	Process costs
	Performance	-	-	Empty run distances and exceeded deadline as penalties	Punctuality of delivery, transport duration, waiting time
	Ergonomics	-	-	-	-

While performance and cost aspects have been extensively integrated into different dynamic resource allocation models, ergonomics has not been sufficiently considered among the relevant criteria used to steer the optimization of the resource allocation process, as summarized in Table I. As anticipated, ergonomics, already a well-established driver for process design and resource configuration especially in the automotive industry [30], has increasingly gained importance in logistics operations [18]. This is true not only as a factor to be included in the definition of the target system [19], but also as a relevant criterion, together with performance and economic convenience, for evaluating the successful adoption of innovative logistic systems [31]. In some cases, ergonomically relevant KPIs already found application in static resource allocation models for operations [32].

For these reasons, also dynamic resource allocation models should take into account ergonomics, together with performance and economic convenience related parameters, as highlighted in Fig. 1. Since the aim of this work is to present an innovative method to include ergonomics in dynamic resource allocation models, a hint on ergonomics and its relevant KPIs in logistics scenarios is hereafter given.

B. *Ergonomics in logistics*

Ergonomics is a scientific discipline, belonging to a sub-area of work science, which applies theory, principles, data and methods to the design process, in order to optimize human well-being, preserving the overall system performance [33].

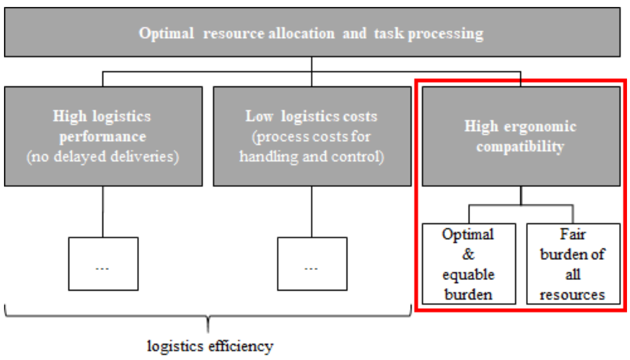

Fig. 1 Objective system for dynamic resource allocations

The International Ergonomics Association [34] defines three sub-types of ergonomics: (1) physical, (2) cognitive and (3) organizational. Physical ergonomics, most common association with the term ergonomics, is concerned with human anatomical, anthropometric, physiological and biomechanical characteristics as they relate to physical activity. Cognitive ergonomics focuses mental processes, such as perception, memory, reasoning, and motor response. Organizational ergonomics is concerned with the optimization of sociotechnical systems, including their organizational structures, policies, and processes [33]. While cognitive aspects have been always widely considered when designing logistics processes, physical stress has recently gained more attention, especially due to the growth of e-commerce. Demanding requirements for fast delivery and increasing throughputs have led, especially during peak seasons, to relatively hard and frenetic working conditions for operators. The existing relation between constant metabolic effort, exhaustion and health risks [35][36], combined with the impact on performance, raised the need for further studies on the topic. One example of these efforts is the analysis and deployment of logistic manual processes into sub-processes and actions by Günthner and Koch [37]. According to this work, every manual process could be described by a combination of lifting, holding, carrying, pulling and pushing activities. For instance, a generic handling process could be decomposed into lifting, holding and carrying (LHC), while a conveying process could be seen as a combination of pushing and pulling activities (PP). Together with the detailed process analysis, several studies on evaluation models for ergonomics have been conducted with the aim of assessing the ergonomic risk, in order to include ergonomics in the decisional process for resource allocation. One such example is the method based on the average required metabolic energy, expressed in kcal/min, proposed by Garg [38], which is based on the assumption that every manual process could be deployed into single activities. This method provides for each process a resource-related metabolic cost. The metabolic cost is therefore different for every single human resource that could be assigned to a specific task, depending on individual characteristics of the resource such as strength, frequency of execution, posture, technique, and body weight. The calculated ergonomic cost could be considered among the criteria to evaluate the ergonomic risk and integrated into a decision model, as suggested by Calzavara et al. [36]. Other approaches focus on different indicator for the decision of resource assignment. Mainly considering the frequency of task execution as a driver, the NIOSH method (US-National Institute for Occupational Safety and Health [39]) and the two key indicators method for LHC and PP [40] provide thresholds for ergonomics risk values. The former focuses on lifting, holding and carrying (LHC), the latter on LHC, push and pulling (PP). Combining the risk values identified with the Ergonomic Assessment Worksheet method (EAWS) [41] or the Multiple-Load-Tool [42] cumulative loads thresholds for one whole shift could be estimated [35] [37]. However, it should be highlighted, that results based on the EAWS are valid under the assumption that the operator performs the same kind of task during the entire shift [43]. Since this assumption is hardly verified in dynamic logistics environment, this method is not directly applicable to the context, object of this work. The Multiple-Load-Tool allows the assessment of the ergonomic risk of activities combinations (LHC and PP) on the basis of historical data. The risk assessment based on this method does not take into account possible future system states and new combinations of orders and related task sequences. This method is therefore also not adequate for a dynamic allocation of resources using ergonomic considerations as a driver for the allocation. When looking at the same allocation problem from the point of view of the task assignment, an interesting approach is presented by Carnahan et al. (vgl. Carnahan et al., 2000). First, the principle of ergonomic job rotation is introduced; then, the resulting scheduling problem is solved by assigning the jobs to the available resources, so that the ergonomic risk is distributed among the employees. The optimization algorithm makes sure that the overall ergonomic load is minimized for employees who are exposed to a high ergonomic risk, taking into account parameters such as weight, repetition, frequency and lifting height.

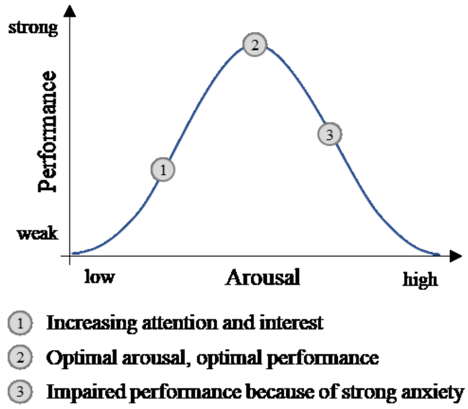

Fig. 2 Worker's performance according to different arousal levels [46]

Generally, all the methods and approaches here summarized tend to minimize the risk of high physical workload. One may think logical to avoid high physical workload for obvious reasons of overload by physical stress tied to the aspects of physical ergonomics; although this is true, it is important to not overlook the possible psychological impact of being on the other side of the spectrum, namely in a situation where the physical workload is too low. This could decrease the engagement of the operator in the task at hand, which in turn could lead to boredom [44] and low situation awareness [45]; these are all aspects that hinder the overall performance of a sociotechnical system. The correlation is shown in Fig. 2. According to this model [46], a high level of arousal causes lower operator performance due to over-engagement and ultimately to stress; performance is weak also if arousal is too low, which in turn can cause under-engagement and boredom. Since the maximum overall performance for operators is obtained in the middle of the inverse U curve, a *balanced* workload should the target for physical and cognitive ergonomics in the allocation of resources.

III. Method

In this chapter, an innovative approach to consider ergonomics in dynamic resource allocation models is presented. Given that ergonomics is only one of the optimization criteria and that it should be considered together with cost and performance [32], the following approach proposed is valid under one main assumption, namely that after a sufficiently long break, as the one between two subsequent shifts, an operator fully regenerates. This enables the assessment of the ergonomic risk in an independent fashion for each single shift [43].

A. Monitoring ergonomic stress

In order to consider the whole spectrum of tasks combination (LHC and PP), the approach proposed by Garg [38], based on the energy consumption, is a fundamental element of the method designed. Since the ergonomic burden related to manual activities (LHC and PP) could be converted into an energy consumption value (kcal), the maximum thresholds of tolerated load handled per shift (kg/shift) could be translated into energy consumption limit per shift (kcal/shift). This means that even if guidelines and regulation are expressed in other unit of measurements, the conversion could always occur, supporting compliancy between the presented method and existing regulations. The energy consumption approach is also particularly suitable for application in scenarios, where both the nature of tasks and the types of unit loads to be handled are heterogeneous. This widens considerably the applicability of the method proposed to a larger set of different scenarios. The maximum ergonomic burden, however, does not only depends on the type of unit loads and their weight, but also on the time interval between manual activities (or its inverse indicator, the frequency), as supported by the key indicator method [47] and Hettinger's table [48]. Heavier physical effort presumably requires longer time for recovery. Following this principle would lead to even and distributed, rather than to erratic and concentrated manual tasks allocation. The temporal dimension of the distribution of tasks should therefore be included in dynamic resource allocation process, together with the effort needed to accomplish one singe task and the already identified limits on the maximum cumulative effort during one shift.

For the above-mentioned reasons, any method aimed at considering all the summarized aspects must first identify the optimal relation between time and energy consumption (hereafter-called *optimal ergonomic burden*) during one shift, under the limitation provided by regulations or internal guidelines. The resource allocation can then follow, considering at the given time, among other model-related drivers, the *deviation* between the optimal ergonomic burden and the *actual* ergonomic burden of each resource. The methodical fundament of the presented approach is rooted in the principles of *critical chain* project management [49], where the remaining buffer available, in terms of time available to complete the critical chain activities before a delay could occur, and the project progress are the two variables considered to assign priorities and resources to different projects or project activities. As introduced by Techt and Lörz [49] a project progress diagram could be used to visualize what progress (in percent) has been made on the critical chain and what percentage of the available buffer (remaining time to delivery) has been consumed. The project or project activity with the highest ratio between buffer-consumption and project-progress would be the most critical one and therefore would deserve more attention, i.e. resources. In other words, being the ultimate goal to finish the projects or projects activities within the given deadline thereby avoiding extra cost due to delays, this approach enable focusing resources on the projects with lower completion status and closer deadline. This logic is fully transferable to the dynamic resource allocation problem, where the project progress represents the elapsed time based on the shift duration, and the consumption of available buffer represents the actual ergonomic burden of a specific resource. The resource with the highest ratio between ergonomic burden and elapsed time on the shift duration deserves more attention, i.e. less ergonomically demanding tasks. This approach in project managements enables the optimal employment of resources balancing the potential costs of over-allocation (namely a reduced capacity in output of projects per year) with those of under-allocation (namely potential delivery delays linked to financial penalties or unsatisfied customers). Similarly, in its application to the dynamic allocation of resources within a working shift, the approach enables the optimal employment of resources balancing the potential costs of over-allocation (namely higher costs of labor for the achieved productivity leading to lower margins) with those of under-allocation (namely potential stress for the operators and consequent high turnover, compensated e.g. with increased salaries). The critical chain method for project management uses a traffic light logic to identify the project activities at risk of delays; in the context of the presented method, the goal would be to follow as close as possible the identified target function, which describes the optimal ergonomic burden distribution during a shift. The resulting diagram, illustrated in Fig. 3, allows the estimation of the actual economic burden of a resource at any given time and thus the deviation from the target function $f_{targ}(r_x)$. As it can be observed in the example of Fig. 3, Resource 1 (Fig. 1, R1) at the beginning of its shift, has already accomplished ergonomically weary activities. In order to reduce the gap between the target function (optimal ergonomic burden) and actual state (actual ergonomic burden), Resource 1 (R1) should make a pause or be assigned to less ergonomically weary activities. Resource number 2 (R2) can keep up working at the given pace and resource number 3 (R3) should be assigned to more challenging tasks, given the low actual ergonomic burden, in respect to the target function. The s-shape of the target function, which defines the temporarily right level of ergonomic stress, is discussed in the following section.

B. The optimal level of ergonomic stress in relation to the elapsed time

The target cumulative energy consumption at the end of the shift could be defined according to regulations or internal guidelines. The level of ergonomic stress that is *right* or *optimal* at any given time and the related objective function should be defined, as previously mentioned, considering the ergonomic burden, measured in calories, since the type of ergonomic stress could differ in intensity, frequency and kind during a shift. Hence, the resource should be allocated to tasks that guarantee an equal distribution of the ergonomic burden, over the whole shift duration. Although one may think that this function could be linear, thus generating a line passing through the origin of the graphic in Fig. 3 and the maximum

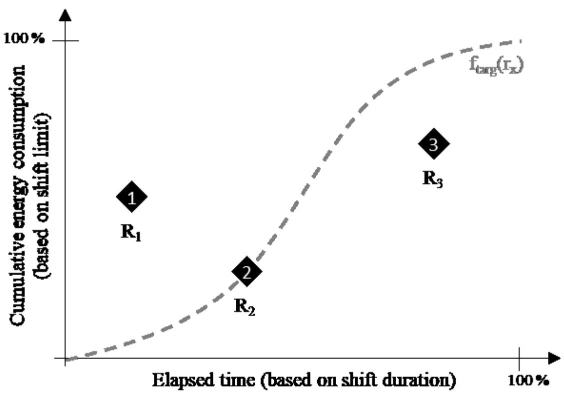

Fig. 3 Ergonomic Diagram

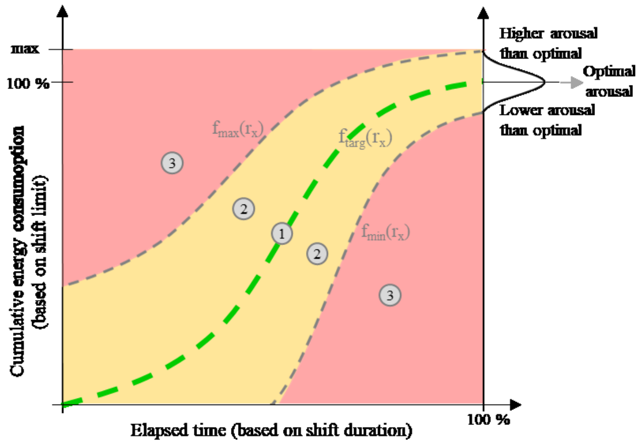

Fig. 4 Ergonomic stress control diagram

cumulative ergonomic burden at the end of the shift, the human behavior and performance in relation to the time, should be considered. Accordingly to different studies [50] [51], the productivity of a human resource, generally culminate in the middle of the shift, as if the human body would need a "warm-up" and a "cool-down" phase. Therefore, the ergonomic burden should be higher in the middle of the shift and lower at the beginning and at the end of it. For this reason, the target function results in an S-shaped, with a steeper slope in the middle of the shift. The exact course of the curve, could also be tailored on the specific resource, if needed, keeping the general S-shape function as a reference. In order to provide a simple way to visualize and track the ergonomic burden of a resource during a shift, it is possible to combine the performance-arousal-diagram represented in Fig. 2, with the ergonomic diagram in Fig. 3. Legal limitations and mandatory standards could be considered to define the upper threshold, while a resource specific performance-arousal-diagram could be adopted to estimate the target function and the lower thresholds. When upper and lower acceptable thresholds have been defined, it is also possible, as suggested by Techt and Lörz [49], to assign a color to each area identified. Fig. 4 illustrates the proposed control diagram, where the green function $f_{targ}(r_x)$ (Fig. 4, 1) represents the target function that should be followed by any given resource. Yellow areas (Fig. 4, 2) represent acceptable areas, characterized respectively lower-than-optimal or higher-than-optimal levels of actual ergonomic burden. The distance between the target function and lower ($f_{min}(r_x)$) or upper ($f_{max}(r_x)$) thresholds is wider in the beginning of the shift given the longer time horizon remained in a shift that is available to take corrective actions. The red areas (Fig. 4, 3) represent the areas above or under the defined lower or upper thresholds. Should a resource appear in the red areas during a shift, an immediate intervention is required to lower or increase the ergonomic burden before the shift is over.

C. The assignment problem model considering ergonomics

When the proposed model is applied, the dynamic resource assignment problem considering ergonomics could be translated into estimating which resource allocation combination brings the highest advantage, in terms of minimum deviation between the value of the target function and the actual ergonomic burden. At a given elapsed time t, for every resource i, the deviation (ΔE_i), between the value of the target function $E_{targ,i}$ and the actual cumulative ergonomic burden E_i could be estimated.

$$\Delta E_i = E_{targ,i} - E_i \tag{1}$$

Fair working conditions for all the resources and equable burden, which should be the goal of a dynamic resource allocation scheduler, could be theoretically achieved, when, for every resource during the whole shift, the difference between target function and cumulative energy consumption, or ergonomic burden, is equal to zero ($\Delta E_i = 0$). Since there is no chance of assuring such a perfect system behavior, especially in dynamic environments, the goal for a dynamic resource allocation scheduler, should be slightly modified. React, as fast as possible, to system disturbances, prioritizing the resource allocation, in order to minimize the total metabolic cost Z, which represent the overall deviation considering the impact of the tasks to be assigned to the resources, thus the projected ergonomic burden.

The mathematical model for this specific assignment problem uses the binary decisional variable x_{ij} and could be led back to a classic assignment problem [25].

$$x_{ij} = \begin{cases} 1 & \text{if resource } i \text{ performs taks } j \\ 0 & \text{if not} \end{cases} \tag{2}$$

Given a combination of an admissible resource-task allocation, Z represents the total projected metabolic deviation in terms of ergonomic burden, at the time of task completion. Projected means that the function Z is an estimation of the future total deviation from the target function, after the resources have carried out the tasks they have been assigned to. The assignment problem could be described as follows.

$$\text{Minimize } Z = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} x_{ij} \tag{3}$$

Subject to

$$\textstyle\sum_{j=1}^{m} x_{ij} = 1 \qquad \text{for } i = 1,2, \dots, \text{m}, \tag{4}$$

$$\textstyle\sum_{i=1}^{n} x_{ij} = 1 \qquad \text{for } j = 1,2, \dots, \text{n}, \tag{5}$$

The first set of functional constraints specifies that a resource i is to perform exactly one task and the second that each task is to be performed by exactly one resource. Since the binary restriction could be deleted without affecting the validity of the results, this assignment problem could be solved as a linear programming problem. In order to adapt this model to a real case study, where most likely $n \neq m$, it is possible to reformulate the problem as convenient, for example by introducing so called *dummy resources* or *dummy tasks.*

The peculiarity of this model lies in the calculation of the projected ergonomic cost c_{ij}.

$$c_{ij} = e^{|\Delta E_i + E_{ij}|} \tag{6}$$

Where E_{ij} represents the ergonomic burden of the task j to be assigned, when carried out by the resource i. The module ensures that both positive and negative projected deviation from the target function are equally considered, while the exponential function ensures that the higher the distance from the target function, the higher would be the impact on the total projected metabolic deviation Z, exponentially discouraging ergonomic overload.

IV. Discussion and Outlook

This paper aims to introduce a model to monitor the ergonomic burden of the resources during a shift and to provide a linear optimization model to steer the resource allocation process. Especially in dynamic logistics environments, where the cumulative ergonomic burden of a single resource during one shift is not exactly foreseeable, monitoring its evolution and allocating accordingly the resources to the most appropriate tasks is fundamental to ensure fair working conditions.

A crucial aspect to consider in order for the method to be applied successfully in a real-world context is the frequency of the monitoring and the consequent decision-making for resource allocation. Even if high digitalization levels of a target implementation context would allow a continuous monitoring and therefore a real-time optimization of the task allocation, the unpredictability of the demand and its implications for ergonomically relevant tasks, typical of demanding intralogistics scenarios, may affect the potential benefits of a continuous monitoring and optimization. For these reasons, two main approaches could be mentioned to steer the optimization process, in order to reach a compromise between the number of resources to be assigned and the tasks to be carried out allowing a certain leeway in distributing the available resources on the tasks for optimization:

1) Fixed time frame and frozen schedule

The allocation process is performed according to a fixed timeframe. During the time interval between two allocation processes, tasks will be collected, without being assigned. The allocation of the available resources to the tasks collected during the time interval occurs at the end of each time interval. The schedule remains frozen for the whole duration of the given time interval.

2) Dynamic - Event oriented

The allocation process is triggered by a specific event, as for instance a new task has to be assigned. Since the allocation principle does not follow a FIFO (first in first out) logic and the schedule is not frozen over a fixed time window, every time an event occurs, the allocation process should be repeated. Together with the new task, all the tasks already assigned to a resource, but not started yet, are considered for a new possible assignment. The resources that could accomplish the task on time are considered available, even if they are currently busy. The ergonomic burden, caused by the currently performed task, is included in the calculation of the actual ergonomic burden of the specific resource.

Determining which approach brings the highest benefit, in terms of minimizing the overall deviation between target function and actual cumulative ergonomic burden, does not fall within the scope of this work and depends on the characteristics of the scenario. However, it is an interesting point that could be examined in future research. Especially, the relations between context characteristics and optimization approach should be investigated. In this regard, the impact of considering different teams of resources and service robots plays a non-negligible role towards logistics efficiency. Performance and convenience related parameters should also be considered together with ergonomics when optimizing the resource allocation. Therefore, the model proposed in this paper is complete for what concern the ergonomic aspects of the allocation process, but not comprehensive, since performance and convenience parameters are not yet taken into account. Developing a comprehensive model to assess all the relevant parameters, thus allowing a multi-criteria dynamic resource allocation in advanced intralogistics scenarios, should steer the upcoming research. Another aspect to investigate further, in relation to the objective function presented in the method chapter, is the possibility to assign a non-linear penalty to tasks that, if assigned/not assigned to a resource, would push it above/below the acceptable thresholds of $f_{max}(r_x)/f_{min}(r_x)$. This potential improvement has been identified and it will be further investigated by the authors of this paper.

V. Conclusions

Ergonomics became a one-dimensional quality attribute of logistic operations and therefore it should be included, along with costs and performance criteria, in resource allocation models. Considering ergonomics in the process of resource allocation is particularly relevant in dynamic intralogistics scenarios, where complex systems of systems are in place, in order to assure fair working conditions. After presenting a review on established dynamic resource allocation models and ergonomics in intralogistics scenarios, the research gap was identified. A novel method, based on the principles of critical chain project management and the assignment problem model was introduced. The ergonomic burden of each resource subjected to potential ergonomic stress is monitored throughout a period of time (shift) and the collected data are used to steer and optimize the resource allocation process. Limitations of the method were discussed and recommendations for future research highlighted. The presented novel approach is intended to be a first step towards a comprehensive multi-criteria and dynamic resource allocation model for complex and advanced intralogistics scenarios.

References

[1] International Federation of Robotics, "Executive Summary - World Robotics 2020 Service Robots." pp. 11–12, 2020.

[2] W. Günthner, J. Durchholz, E. Klenk, and J. Boppert, Schlanke Logistikprozesse. 2013.

[3] W. Kersten, M. Seiter, B. von See, N. Hackius, and T. Maurer, Trends und Strategien in Logistik und Supply Chain Management – Chancen der digitalen Transformation. Bremen: Bundesvereinigung Logistik (BVL), 2017.

[4] J. Schuhmacher and V. Hummel, "Development of a descriptive model for intralogistics as a foundation for an autonomous control method for intralogistics systems," in 8th Conference on Learning Factories 2018 - Advanced Engineering Education & Training for Manufacturing Innovation, 2018, vol. 23, no. 2017, pp. 225–230.

[5] H. Wiendahl and H. Wiendahl, Betriebsorganisation für Ingenieure, 9th ed. Hanser, 2019.

[6] S. Steinau, K. Andrews, and M. Reichert, "Modeling Process Interactions with Coordination Processes," Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics), vol. 11229 LNCS, pp. 21–39, 2018.

[7] B. P. Gerkey and M. J. Matarić, "A formal analysis and taxonomy of task allocation in multi-robot systems," Int. J. Rob. Res., vol. 23, no. 9, pp. 939–954, 2004.

[8] D. Rivas and L. Ribas-Xirgo, "Agent-based Model for Transport Order Assignment in AGV Systems," IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA, vol. 2019-Septe, pp. 947–954, 2019.

[9] M. Bonini et al., "Automation of Intralogistic Processes through Flexibilisation - A Method for the Flexible Configuration and Evaluation of Systems of Systems," in ICINCO 2018 - Proceedings of

the 15th International Conference on Informatics in Control, Automation and Robotics, 2018, pp. 390–398.

[10] W. Günthner and M. ten Hompel, Internet der Dinge in der Intralogistik. Springer, VDI, 2010.

[11] H. Martin, Transport- und Lagerlogistik: Systematik, Planung, Einsatz und Wirtschaftlichkeit. Springer Vieweg, 2016.

[12] W. A. Günthner, R. Chisu, and F. Kuzmany, "Trends und Perspektiven in der Intralogistik-15. Deutscher Materialfluss-Kongress"" Intralogistik-Heute-Morgen-Übermorgen," in VDI-Berichte 1928, 2006.

[13] M. ten Hompel and M. Henke, "Logistik 4.0," in Industrie 4.0 in Produktion, Automatisierung und Logistik, vol. 1, no. 1, T. Bauernhansl, M. ten Hompel, and B. Vogel-Heuser, Eds. Springer Vieweg, 2014, pp. 615–624.

[14] J. Schuhmacher and V. Hummel, "Self-organization and autonomous control of intralogistics systems in line with versatile production at Werk150," pp. 157–166, 2020.

[15] J. G. Erdmann, V. Hummel, K. von Leipzig, and J. Schuhmacher, "Development and implementation of an autonomous control system for target-optimised use of intralogistics transport systems in the learning factory werk 150 at Reutlingen University," Procedia Manuf., vol. 45, pp. 405–410, 2020.

[16] M. Bonini, D. Prenesti, A. Urru, and W. Echelmeyer, "Towards the full automation of distribution centers," in 2015 4th IEEE International Conference on Advanced Logistics and Transport, IEEE ICALT 2015, 2015.

[17] M. Dewitz, S. Galka, and W. A. Günthner, "Drive-Thru Loading Concept for In – Plant Milk Runs," in Proceedings of XX International Conference MHCL ´12, 2012, pp. 6–6.

[18] W. a. Günthner, S. Galka, E. Klenk, T. Knössel, and M. Dewitz, Stand und Entwicklung von Routenzugsystemen für den innerbetrieblichen Materialtransport: Ergebnisse einer Studie. Technische Universität München, 2012.

[19] D. T. Roy, "Industrie 4.0 – Gestaltung cyber-physischer Logistiksysteme zur Unterstützung des Logistikmanagements in der Smart Factory." p. 126, 2017.

[20] W. Domschke and A. Scholl, Logistik: Rundreisen und Touren. Walter de Gruyter GmbH & Co KG, 2014.

[21] M. Steglich, D. Feige, and P. Klaus, Logistik-Entscheidungen: Modellbasierte Entscheidungsunterstützung in der Logistik mit LogisticsLab. Walter de Gruyter GmbH & Co KG, 2016.

[22] D. Vahs and J. Schäfer-Kunz, Einführung in die Betriebswirtschaftslehre. Schäffer-Poeschel, 2015.

[23] T. Plümer and E. Steinfatt, Produktions-und Logistikmanagement. Walter de Gruyter GmbH & Co KG, 2016.

[24] Verein Deutscher Ingenieure, "VDI 2525 - Practice-oriented characteristic values for logistics in small and medium-sized companies," no. July. 1999.

[25] F. S. Hillier and G. J. Lieberman, Operations Research, 9th ed. McGraw-Hill, 2010.

[26] W. Domschke and A. Scholl, "Logistik: Rundreisen und Touren. 5. Auflage Hrsg." München: Oldenbourg Wissenschaftsverlag GmbH, 2010.

[27] B. P. Gerkey and M. J. Mataric, "A Formal Analysis and Taxonomy of Task Allocation in Multi-Robot Systems," Int. J. Rob. Res., vol. 23(9), no. 9, pp. 939–954, 2004.

[28] D. P. Bertsekas, "The auction algorithm for assignment and other network flow problems: A tutorial," Interfaces (Providence)., vol. 20, no. 4, pp. 133–149, 1990.

[29] M. Mirlach, W. A. Günthner, A. Ulbrich, and K. Beckhaus, "Auftragszuteilungsverfahren für Staplerleitsysteme," in 17. Flurförderzeugtagung 2013, 2013.

[30] N. Boysen, S. Emde, M. Hoeck, and M. Kauderer, "Part logistics in the automotive industry: Decision problems, literature review and research agenda," Eur. J. Oper. Res., vol. 242, no. 1, pp. 107–120, 2015.

[31] W. A. Günthner and C. Keuntje, "IntegRoute – Ganzheitliche Konzeptauswahl für Routenzugsysteme zur Produktionsversorgung," 2016.

[32] M. Bonini, J. Schuhmacher, A. Urru, J. P. Wezel, V. Hummel, and W. Echelmeyer, "Planning of Available Resources Considering Ergonomics Under Deterministic Highly Variable Demand," in 2020 IEEE International Conference on Industrial Engineering and Engineering Management, 2020, pp. 96–102.

[33] F. Tosi, Design for Ergonomics. Cham: Springer, 2020.

[34] A. Chapanis, "The international ergonomics association: its first 30 years," Ergonomics, vol. 33, no. 3, pp. 275–282, 1990.

[35] E. H. Grosse, M. Calzavara, C. H. Glock, and F. Sgarbossa, "Incorporating human factors into decision support models for production and logistics: current state of research," IFAC-PapersOnLine, vol. 50, no. 1, pp. 6900–6905, 2017.

[36] M. Calzavara, C. H. Glock, E. H. Grosse, A. Persona, and F. Sgarbossa, "Analysis of economic and ergonomic performance measures of different rack layouts in an order picking warehouse," Comput. Ind. Eng., vol. 111, pp. 527–536, 2017.

[37] W. A. Günthner and M. Koch, "Ergo-Jobrotation--Planungsmethodik für eine ergonomisch optimale Jobrotation in der Intralogistik," 2016.

[38] A. Garg, D. B. Chaffin, and G. D. Herrin, "Prediction Of Metabolic Rates For Manual Materials Handling Jobs," Am. Ind. Hyg. Assoc. J., vol. 39, no. 8, pp. 661–674, 1978.

[39] S. L. Sauter, L. R. Murphy, and J. J. Hurrell, "Prevention of work-related psychological disorders: A national strategy proposed by the National Institute for Occupational Safety and Health (NIOSH).," Am. Psychol., vol. 45, no. 10, p. 1146, 1990.

[40] German Ordinance on Occupational Health Care, "Key Indicator Method for assessing and designing physical workloads with respect to manual Lifting , Holding and Carrying of loads ≥ 3 kg KIM-LHC." BAuA/ASER/ArbMedErgo/ebus, 2019.

[41] K. G. Schaub et al., "Ergonomic assessment of automotive assembly tasks with digital human modelling and the 'ergonomics assessment worksheet'(EAWS)," Int. J. Hum. Factors Model. Simul., vol. 3, no. 3–4, pp. 398–426, 2012.

[42] K. Schaub et al., "Das Multiple-Lasten-Tool: integrierte Bewertung unterschiedlicher Arten manueller Lastenhandhabung," 2010.

[43] A. Otto and A. Scholl, "Reducing ergonomic risks by job rotation scheduling," OR Spectr., vol. 35, no. 3, pp. 711–733, 2013.

[44] M. R. Endsley and E. O. Kiris, "The Out-of-the-Loop Performance Problem and Level of Control in Automation," Hum. Factors J. Hum. Factors Ergon. Soc., vol. 37, no. 2, pp. 381–394, 1995.

[45] J. a Adams, "Human-Robot Interaction Design: Understanding User Needs and Requirements," Proc. Hum. Factors Ergon. Soc. 49th Annu. Meet. {O}rlando, {FL}, {USA}, no. 3, pp. 447–451, 2005.

[46] D. M. Diamond, A. M. Campbell, C. R. Park, J. Halonen, and P. R. Zoladz, "The temporal dynamics model of emotional memory processing: A synthesis on the neurobiological basis of stress-induced amnesia, flashbulb and traumatic memories, and the Yerkes-Dodson law," Neural Plast., vol. 2007, 2007.

[47] Deutsche Gesetzliche Unfallversicherung E.V. (DGUV), "DGUV Information 209-015." Deutsche Gesetzliche Unfallversicherung Spitzenverband, 2018.

[48] T. Hettinger and G. Wobbe, Kompendium der Arbeitswissenschaft: Optimierungsmöglichkeiten zur Arbeitsgestaltung und Arbeitsorganisation. Kiehl Ludwigshafen, 1993.

[49] U. Techt and H. Lörz, Critical Chain-inkl. Arbeitshilfen online: Beschleunigen Sie Ihr Projektmanagement. Haufe-Lexware, 2014.

[50] E. Facer-Childs and R. Brandstaetter, "The impact of circadian phenotype and time since awakening on diurnal performance in athletes," Curr. Biol., vol. 25, no. 4, pp. 518–522, 2015.

[51] C. Schlick, R. Bruder, and H. Luczak, Arbeitswissenschaft. Springer-Verlag, 2018.