36th European Modeling & Simulation Symposium, 036
21th International Multidisciplinary Modeling & Simulation Multiconference

2724-0029 © 2024 The Authors.
doi: 10.46354/i3m.2024.emss.036

Towards Real-Time Task Allocation in Human-Robot Collaboration: Defining Key Requirements and Features for a Multi-Simulation Digital Twin System

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Abstract

The Fourth Industrial Revolution, or Industry 4.0, introduces transformative changes in manufacturing by integrating advanced digital technologies, with Human-Robot Collaboration playing a central role. This paper conducts a comprehensive literature review to identify critical research gaps in the field of Human-Robot Collaboration within the context of Industry 4.0, focusing on task allocation between humans and robots in assembly lines, and defines key requirements and features necessary for developing a multi-simulation-based Digital Twin. The review reveals that existing studies often adopt a fragmented approach, concentrating either on productivity or ergonomic aspects without integrating them holistically. Additionally, it highlights the inconsistent use of ergonomic methodologies and the lack of real-time, operator-driven solutions in current Digital Twin models. These gaps are addressed by key requirements and features necessary for developing a multi-simulation-based Digital Twin system that optimizes task allocation in Human-Robot Collaboration environments. The identified requirements include the integration of ergonomic and productivity data, real-time data exchange capabilities, and the use of established ergonomic methodologies.

Keywords: Human-Robot Collaboration; Digital Twin; Ergonomics; Smart Operator; Multi-Simulation;

1. Introduction

The Fourth Industrial Revolution, or Industry 4.0, marks a significant transformation in the way manufacturing industries operate, integrating advanced digital technologies to create smarter, more efficient, and interconnected systems. Central to this evolution is Human-Robot Collaboration (HRC), a paradigm that promotes the integration of human workers and robotic systems to enhance operational efficiency and workplace safety (Thoben et al., 2017). HRC emphasizes the importance of direct interaction between humans and robots, leveraging the strengths of both to achieve a higher level of productivity and innovation (Baratta et al., 2023). The collaborative robot market is experiencing significant growth. In 2023, the global collaborative robots market size was valued at $1.58 billion, and it is forecasted to reach $11.04 billion by 2030, growing at a compound annual growth rate (CAGR) of 32.0% from 2023 to 2030. This growth is driven by the increasing adoption of collaborative robots in various applications and sectors

(Şahan et al., 2023). The integration of robots into production lines, particularly in assembly processes, hinges significantly on the use of simulation technologies (Zhang et al., 2019). Simulation serves as a tool, enabling scenario analysis, layout management of workstations, and optimization of workflows (Casanova et al., 2020; Baratta et al., 2024). Through simulation, manufacturers can plan and execute the incorporation of robotic systems, ensuring operations and enhanced productivity. This approach not only facilitates the precise evaluation of potential operational impacts but also allows for the strategic planning of physical space and human-robot interactions. Consequently, simulations act as a bridge between theoretical planning and practical implementation (Dobrescu et al., 2019). Over the last years, even the concept of multi-simulation is gaining momentum. Multi-simulation refers to the use of multiple simulation models interacting with each other to replicate different aspects of manufacturing processes, including physical, operational, and human factors. In HRC contexts, multi-simulation enables the comprehensive analysis of interactions between human workers and robots, assessing the efficiency and productivity of these collaborations as well as the ergonomics and safety aspects which are crucial for worker wellbeing (Bellini et al., 2021). In addition, given the complexities that a collaborative scenario brings to the table, real-time monitoring of production line activities is also becoming increasingly important. This emphasis on real-time insight allows for immediate identification and resolution of issues, enhancing operational efficiency and reducing downtime (Ogunsakin et al., 2023). With this regard, Digital Twins (DTs) serve as dynamic, virtual replicas of physical systems, allowing for the simulation, prediction, and optimization of processes in real-time (Murgod et al., 2023; Baratta et al., 2024b). In the realm of HRC, DTs offer the capability to simulate human-robot interactions in a virtual environment, enabling the identification and resolution of potential issues before they occur in the physical world (Malik & Bilberg, 2018). This predictive capability is vital for minimizing downtime, enhancing production efficiency, and ensuring the safety of human workers.

By leveraging advanced simulations in a DT perspective, stakeholders can effectively ensure that the interactions between humans and robots optimize operational efficiency and actively promote a supportive and injury-free working environment. Importantly, even operators can directly test various simulated scenarios, monitor real-time production and ergonomic metrics in response to changes in human-robot task allocation. The culmination of this concept, representing a forward-thinking approach within the manufacturing sector, leads to the emergence of the Smart Operator (O4.0), a role that embodies the integration of human intelligence with digital technologies (Longo et al., 2017). O4.0 initiatives in HRC scenarios are focused on empowering human workers to work seamlessly alongside robots, leveraging the strengths of both human flexibility and robotic precision (Longo et al., 2017).

The paper carries out a comprehensive literature review of the topic and defines key requirements and features for a multi-simulation-based Digital Twin system aimed at optimizing task allocation between humans and robots in assembly lines. The system should integrate ergonomic and productivity considerations, supports real-time data exchange, and empower operators through a user-friendly interface for dynamic task management.

The reminder of the paper consists of Section 2, reviewing the literature and identifying gaps; Section 3, introducing the methodology for developing the proposed DT, including system requirements and features; Section 4, outlining the multi-simulation based DT key requirement and features; Section 5, focusing on conclusions and future research directions.

2. Literature Review

The literature review has been carried out by using the PRISMA methodology (Page et al., 2021). The Scopus database has selected as the primary source for this review due to its comprehensive collection of peer-reviewed literature, including scientific journals, books, and conference proceedings (https://www.elsevier.com/products/scopus/content). To analyze the relevant scientific literature, the authors employed a structured query designed to capture a wide range of papers focusing on task allocation within HRC. The query utilized a combination of specific keywords related to HRC, such as "human-robot interaction", "HRI", "HRC", and "Human Robot Collaboration", along with terms associated with "task allocation", including "task distribution", "work allocation", "work distribution", and "line balancing". This approach was chosen to ensure the retrieval of as many papers as possible addressing task allocation in the context of HRC, thereby facilitating a thorough examination of the available literature on the subject. The search initially yielded 226 studies, which were reduced to 224 after excluding those not written in English. Subsequently the selection was narrowed down to journal articles. This screening process resulted in the identification of 98 relevant research works. These articles were then meticulously reviewed, and 30 were selected based on their relevance to this study's research topic, inclusion of case studies, and presentation of application results. The 30 articles formed the basis for analyzing the literature of interest. Figure 1 illustrates the results obtained through the implementation of the PRISMA methodology. Proceeding further with the literature review analysis, the 30 identified articles were systematically categorized based on specific criteria considered essential by the authors to delineate the research framework contextualizing this study. These criteria are detailed as follows.

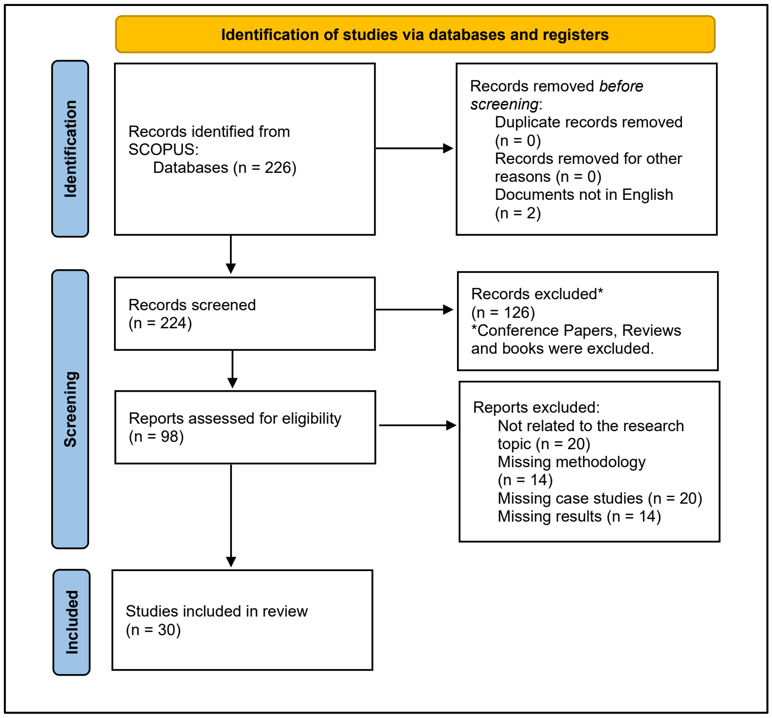

Figure 1. PRISMA methodology application summary

- Productivity: assessing whether the study includes productivity-related KPIs or parameters;
- Ergonomics: evaluating if ergonomic KPIs or parameters were examined in the research;
- DT: identifying if the models presented were developed using a DT approach, indicating the creation of virtual replicas of manufacturing systems for simulation and analysis with real-time data exchange;
- Multi-simulation: determining if multiple simulation models were designed and developed to complement each other, providing a holistic view of HRC scenarios;
- O4.0: investigating if the proposed solutions were designed from an O4.0 perspective, intended either as informative tools for operators directly involved in production or utilities that operators can utilize to gain insights or information directly.

Table 1. Literature review analysis

References	Productivity	Ergonomics	Digital Twin	Multi- Simulation	Smart Operator
Mateus et al. (2020); Çil et al. (2020); Nourmohammadi et al. (2022); Guo et al. (2023); Rabbani et al. (2020); Li et al. (2021); Touzani et al. (2022)	✓				
Lee et al. (2022)	✓				✓
Şahin & Tural (2023); Li et al. (2023); Mao et al. (2023), Wu et al. (2023)	✓			✓	
Zhu et al. (2022)	✓		✓		✓
El Makrini et al. (2019)		✓			
Bilberg & Malik (2019)		✓	✓		✓
Merlo et al. (2023)		✓		✓	✓
Bänziger, Kunz, and Wegener (2020); Dalle Mura & Dini (2021); Alessio et al. (2022); Belhadj, Aicha, and Aifaoui (2022); Liau et al. (2022); Rahman et al. (2023); Faccio, Granata and Minto (2024); Huang et al. (2024); Calzavara, Faccio, and Granata (2023)	✓	✓			
Dalle Mura and Dini (2019); Gjeldum et al. (2022); Messeri et al. (2022); Petzoldt et al. (2022);	✓	✓			✓
Guo (2024)	✓	✓		✓	
Our approach	✓	✓	✓	✓	✓

Table 1 presents the outcomes of the categorization process, highlighting which criteria were satisfied for each paper. The table concludes also by classifying this research study according to these criteria, providing an intuitive overview of how this study contributes to advance the current state of the art.

The analysis of the literature reveals a highly fragmented nature of the studies regarding task allocation in HRC domain. In fact, many studies take a singular approach, focusing either solely on productivity aspects or exclusively on operator ergonomics. Among them, 8 studies predominantly concentrate on optimizing task allocation through conventional methods (Mateus et al., 2020; Çil et al., 2020; Nourmohammadi et al., 2022; Guo et al., 2023; Rabbani et al., 2020; Li et al., 2021; Touzani et al., 2022, El Makrini et al., 2019), while 7 propose innovative approaches based on DT, multi-simulation, and/or O4.0 solutions. Specifically, Lee et al. (2022) introduce an O4.0-based solution to efficiently plan and distribute disassembly tasks between human operators and robots, aiming to minimize disassembly time. Şahin & Tural (2023), Li et al. (2023), Mao et al. (2023) and Wu et al., (2023) adopt multi-simulation solutions based on innovative mathematical programming techniques. Zhu et al. (2022) stand out as the sole study focusing on task allocation from a productivity perspective, presenting a method for dynamic reconfiguration optimization in intelligent manufacturing systems with HRC, utilizing a DT approach within an O4.0 framework. Additionally, Bilberg & Malik (2019) propose an O4.0 DT solution tailored for dynamic task allocation and robot trajectory optimization, specifically addressing dexterous assembly tasks. Furthermore, Merlo et al. (2023) present an O4.0-centered multi simulation model achieved through the integration of two distinct models: one addressing the task allocation problem and the other assessing ergonomic risk with the aim of reducing musculoskeletal disorders.

Several have been also the research attempts to face task allocation issue in HRC context by simultaneously considering both ergonomics and productivity aspects.

The majority of these efforts adopt traditional methodologies to achieve task allocation objectives. In these cases, it has been observed that the accuracy of ergonomic analyses often relies on mathematical models calibrated for specific case studies, which may be challenging to replicate on a large scale or easily. These mathematical models have been proposed to tackle human-robot task allocation issues across various contexts, including specific assembly lines at the Volkswagen plant in Wolfsburg (Bänziger et al., 2020), handling bulky and heavy parts (Dalle Mura & Dini, 2021), mold assembly lines (Liau and Ryu, 2022), two-stage snow plough mill, gear box and self-priming pump assembly processes (Alessio et al., 2022; Belhadj et al., 2022, Calzavara et al., 2023), hard disk drive disassembly procedure (Lee et al., 2022), automobile factory processes (Huang et al., 2024) and generic manipulation of small components (Faccio et al., 2024).

When addressing the task allocation issue through innovative approaches (DT, multi-simulation, O4.0) integrating both productivity and ergonomic considerations, the literature review indicates a significant gap in research efforts.

Currently, there is a lack of research work addressing this topic through DT-based solutions. Existing DT-based solutions tend to focus solely on either productivity (Zhu et al., 2022) or ergonomic aspects (Bilberg & Malik, 2019), with none concurrently considering both aspects. Furthermore, these DT-based solutions are not directly managed by line operators, effectively making them off-(the)-line systems since the results cannot be implemented in real-time or near real-time. Furthermore, the integration of these DT models does not facilitate decision-making processes aimed at optimizing processes based on specific real-time needs arising from human operators. A more effective approach to facilitate the implementation of improved task allocation would be to provide these solutions as on-(the)-line tools directly manageable by operators, ensuring prompt decision-making and swift implementation of results.

In the realm of multi-simulation approaches, the only research work addressing task allocation issues by considering both ergonomics and productivity aspects is that of Guo et al. (2022), thereby underscoring the constrained research efforts in employing this methodology.

The research scenario advances when attention shifts to O4.0-based approaches considering both ergonomic and productivity aspects; however, studies in this area remain limited, with only 4 research articles identified. These studies present O4.0 based solutions, including a genetic algorithm-based method introduced to balance robot efficiency with human ergonomics (Dalle Mura & Dini, 2019), the HUMANT algorithm within a decision support system (Gjeldum et al., 2022), a 3D vision system to estimate muscle fatigue in real-time (Messeri et al., 2022), and performing evaluations through user studies (Petzoldt et al., 2022). These studies, along with those presenting O4.0 solutions considering either ergonomic (Lee et al., 2022; Zhu et al., 2022) or productivity (Bilberg & Malik, 2019; Merlo et al., 2023) aspects, although involving operators for model calibration, completely exclude them from defining constraints and preferences and evaluating the solutions proposed by the systems. It essentially lacks empowerment and accountability for operators directly involved in production processes.

The research landscape in this field is highly fragmented, with a notable absence of holistic approaches to task allocation within HRC framework. Despite advancements in individual methodologies, there's a critical need for integrated solutions that consider both productivity and ergonomic aspects simultaneously, empowering operators and ensuring effective decision-making in real-time production environments.

Section 2.1 provide a summary of the identified research gaps and outline the authors' approach in addressing them with the aim to advance the current state of the art.

2.1. Current research gaps and our approach

Overall, the detected research gaps can be summarized as follows:

- Research gap 1- Fragmented approach to HRC task allocation: despite numerous research works in the field, it becomes evident that these studies exhibit a highly fragmented nature. They typically approach the topic by focusing on either ergonomics or productivity aspects, and even when both are considered, there is a deficiency in the integrated application of innovative approaches such as DT, multi-simulation, and O4.0 solutions. Essentially, the topic has not been addressed holistically, lacking a comprehensive 360-degree perspective. This fragmented approach defines also a significant challenge in effectively managing various data from various sources simultaneously in order to gather information that provides a clear understanding of the assembly processes and their dynamics as a whole.
- Research gap 2: - Inconsistent ergonomic methodologies: the accuracy of ergonomic analyses often depends on the use of mathematical models calibrated on specific case studies, which are difficult to reproduce on a large scale or easily. Consequently, there is a pressing need for the development of a consistent approach. This necessitates the adoption of recognized and shared methodologies as well as commercially available software to ensure reliability and reproducibility across various applications and contexts.
- Research gap 3 - Off-(the)-line system: existing DT based solutions lack direct accessibility for line operators, thus making them as off-(the)-line systems for operators themselves. This disconnection limits the real-time implementation of the results, thus reducing their practical utility.
- Research gap 4 - Lack of operator empowerment in HRC task allocation: despite several studies addressing HRC task allocation issues with an O4.0 perspective, there is a notable lack of systems that enable direct operator engagement. While operators are frequently involved in system calibration, they are often excluded from defining constraints, expressing preferences, specifying their needs, and evaluating proposed solutions. This absence of direct operator involvement significantly restricts their active participation in the decision-making process, potentially leading to misleading solutions implementation.

This paper represents the first step at addressing all the research gaps above mentioned by developing a multi-simulation based DT system that can be used by assembly line operators, with a O4.0 perspective, to effectively manage task allocation between humans and robots, assessing both ergonomic and productivity KPIs simultaneously. The scientific contribution is thus the definition of the DT system key requirements and features. The definition of key requirements and features is a critical step in building the foundations that serve as a guideline for:

- Providing a holistic framework for dynamic task allocation in HRC by integrating various aspects such as ergonomics, productivity, DT, multi-simulation, and O4.0 solutions. Specifically, the authors propose a unified system that incorporates these diverse elements. This system will be directly accessible to operators through a user-friendly interface, allowing them to conduct online simulations in real-time. Operators will have the capability to customize simulations based on production constraints, ergonomics considerations, and current scheduling requirements. Through this application, operators can evaluate KPIs according to their specific needs and preferences. Moreover, the system will empower operators to view insights, enabling them to assess the validity of the configured settings or the solutions proposed by the tool.
- Designing and developing a system based on established and widely recognized methodologies leveraging on commercially available software designed to adhere to these standardized approaches. This strategy is aimed at guaranteeing the reliability and reproducibility of ergonomic analyses across a variety of applications and contexts within the HRC domain.
- Designing and developing a system as an on-(the)-line solution accessible to line operators, thus overcoming the limitation of off-(the)-line systems. This solution enables operators to conduct scenarios simulation in real-time, allowing for dynamic adjustments in task allocation between human operators and robots as production conditions evolve, even in the face of unexpected changes of the boundary conditions.
- Designing and developing a system that empowers operators to define constraints, express preferences, specify needs, and evaluate proposed solutions in alignment with their ergonomics needs and simultaneously without losing sight of fundamental production parameters. This system

enables operators to actively participate in the decision-making process approaching the task allocation issues with a holistic perspective.

3. Methodological Approach

As said, the end goal of the full research is devoted to develop a multi-simulation based DT system that can be used by assembly line operators, with a O4.0 perspective, to effectively manage task allocation between humans and robots, assessing both ergonomic and productivity KPIs simultaneously. The starting point of the research activities has been the definition of the roadmap for designing, developing and validating the multi-simulation based DT system. This roadmap consists of the following steps (Figure 2).

The focus of this paper will be on the first step of this map.

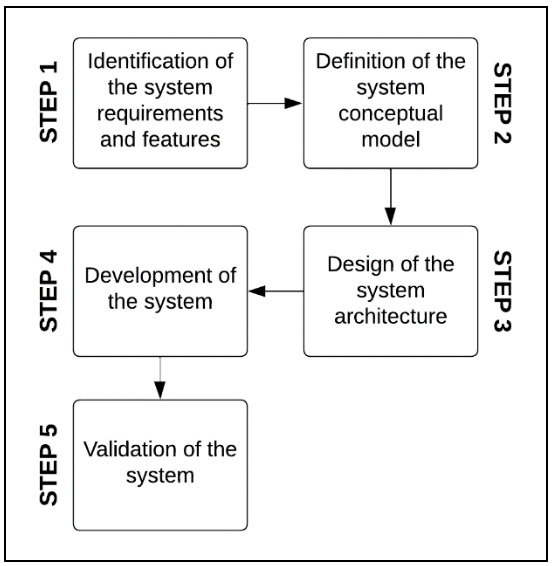

Figure 2. Methodological Approach

STEP 1 - Identification of the system requirements and features: in this initial step, the focus is on identifying the requirements and features essential for the successful development of the multi-simulation based DT system. The goal is to establish a clear understanding of the functionalities and capabilities that the DT system must encompass to effectively support human-robot task allocation by assembly line operators.

STEP 2 - Definition of the system conceptual model: once the requirements and features have been identified, the next step is to define the conceptual model of the DT system. This involves conceptualizing the structure, components, and interactions within the system to facilitate efficient task allocation management. Specifically, the authors leverage on the use of class diagrams to define the static structure of the system and of use case diagrams to illustrate how end-users can interact with the system.

STEP 3 - Design of the system architecture: with the conceptual model in place, the focus shifts to the design of the system architecture. This involves determining the system infrastructure and components needed to implement the DT system. Moreover, it involves defining the operational interactions among the system's various components, as well as between these components and external systems.

STEP 4 - Development of the system: this step transforms the conceptual designs and architectural plans into a working solution. It involves implementing the various components and functionalities and it encompasses a spectrum of tasks from developing assembly line simulation models to create system user interfaces, integrate real-world data, and carry out coding activities for ergonomic and time performance analysis.

STEP 5 - Validation of the system: the final step in the roadmap is to validate the developed DT system. This involves assessing its effectiveness in supporting assembly line operators in managing task allocation between humans and robots while considering both productivity and ergonomic factors.

4. Identification of the system requirements and features

This section delves into the analysis and definition of the requirements and features of the proposed system. The requirements were meticulously identified through a multifaceted approach, which initially involved addressing the research gaps emerged from the analysis of the literature. Moreover, the authors actively engaged with human operators working at the assembly workstation under consideration to gather firsthand insights into their needs and challenges. Furthermore, dedicated meetings were organized with the assembly workstation team leader and managers to capture broader perspectives and performance objectives. By integrating also feedback from these key stakeholders, the requirements were meticulously tailored to accurately reflect operational realities and strategic goals. Subsequently, the authors identified system features that align with these requirements, ensuring that the proposed system effectively addresses the identified research gaps, the needs of the operators along with the considering overall workstation performance and safety. Table 1 provides a summary outlining the identified requirements and the list of features aiming at fulfilling each of them.

Table 2. System Requirements

Requirements
REQ1 - Data integration and management
- The system shall integrate several elements, including ergonomic and productivity aspects along with innovative approaches. - The system shall allow real time data exchange with the real system and between the system elements. - The system shall support a database architecture to handle several types of dynamic data.

- The system shall integrate operator profiles (including anthropometric parameters, experience level, etc.). - The system shall provide continuous data updates between its digital and physical elements.
REQ 2. Ergonomic analysis with comprehensive data utilization
- The system shall employ a specific element for computing ergonomic analysis. - The system shall employ established and recognized ergonomic methodologies. - The system shall employ commercially available software - The ergonomic element shall use operators' anthropometric parameters, component and tool CAD model and weight for an effective ergonomic assessment. - The system shall provide ergonomic assessments reports.
REQ 3. Multi-Simulation Models
- The system shall provide a DES element for simulating production processes. - The system shall allow for what-if simulation and different task allocation scenarios evaluation. - The system shall be adaptable to incorporate production parameters including human operators' characteristics, workflow, robot information, and task execution procedures. - The system settings in the DES element shall be modifiable by the end-user. - The system shall enable the assessment and evaluation of task allocations in real-time.
REQ 4. User-Centric (O4.0) Interface for Simulation Control and Evaluation
- The system shall feature an intuitive user interface. - The system shall enable operators to visualize ergonomic and productivity KPIs, human robot task allocation, and simulation settings. - The system shall enable operators to evaluate assessment reports, accept or decline task allocation scenarios, and customize simulations based on ergonomic and productivity data.

Table 3. System Features

Features
FEAT 1. Comprehensive Data Management
- Modular architecture: utilizing a modular architecture enabling integration of multi-simulation models including an interface for integrating various simulation tools. - Robust data exchange: implementing a robust data exchange system facilitating real-time data exchange between the system modules and from the real system to the modules. - Scalable database: deploying a scalable database architecture capable of efficiently managing dynamic data of various types. - Operator profile management: ensuring the management of different operators' profiles, including anthropometric data, operational status, and experience levels
FEAT 2. Multi-Simulation and Scenario
- Ergonomic simulation module: computing ergonomic simulations using established and recognized ergonomic methodologies and leveraging CAD models and other relevant data to ensure simulation accuracy and effectiveness. - Ergonomic reports generation: producing detailed ergonomic assessment reports to supports operators in their decision-making process regarding human robot task allocation. - Discrete Event Simulation (DES) module: run discrete event simulation to analyze different human robot task allocations scenario and assess their impacts to ergonomic and productivity KPIs - Graphic User Interface (GUI): offering end-users a user-friendly interface to adjust simulation settings and parameters according to their specific requirements and preferences. - Task allocation assessment and evaluation: real-time evaluation of task allocations using current operational data and insights from simulations.
FEAT 3. Interactive Web Application
- User centric interface: adopting a user-friendly and intuitive interface designed to enhance navigation and interaction for all system users. - Enhanced visualization tools: integration of features into the interface, enabling operators to visualize workflows, task allocations, simulation settings, and ergonomic reports with greater clarity and detail. - Interactive simulations control: integrating intuitive buttons into the interface, empowering human operators to customize simulation settings, set evaluation goals, simulate various scenarios to evaluate potential impacts, and take decisions by accepting or declining suggestions.

5. Conclusion

This paper undertakes a comprehensive literature review to identify key gaps in the current research on HRC, particularly focusing on task allocation within Industry 4.0 assembly lines. The findings highlight a highly fragmented research landscape, where studies typically concentrate on either productivity or ergonomic aspects, seldom integrating these two crucial dimensions. Moreover, the review uncovers inconsistencies in ergonomic methodologies and a notable absence of real-time, human-centric DT solutions.

To address these gaps, the paper defines key requirements and features for a multi-simulation-based DT system. The identified requirements include the integration of ergonomic and productivity data, support for real-time data exchange, and the utilization of established ergonomic methodologies. Additionally, the system emphasizes a user-friendly interface that empowers operators to dynamically manage task allocation, allowing for real-time adjustments based on current production conditions.

Future research will focus on developing this holistic framework, integrating various aspects such as ergonomics, productivity, DT, multi-simulation, and O4.0 solutions into a unified system. This system will be directly accessible to operators, enabling them to conduct real-time simulations, customize scenarios based on specific needs, and evaluate the effectiveness of different task allocations. Furthermore, the research aims to design a system that adheres to standardized ergonomic methodologies, ensuring reliability and reproducibility across various applications. By empowering operators with on-the-line tools for dynamic task management, the proposed system seeks to overcome the limitations of current off-the-line solutions, ultimately enhancing decision-making processes in HRC environments.

References

Alessio, A., Aliev, K., & Antonelli, D. (2022). Multicriteria task classification in human-robot collaborative assembly through fuzzy inference. Journal of Intelligent Manufacturing. https://doi.org/10.1007/s10845-022-02062-4

Bänziger, T., Kunz, A., & Wegener, K. (2018). Optimizing human–robot task allocation using a simulation tool based on standardized work descriptions. Journal of Intelligent Manufacturing, 31(7), 1635–1648. https://doi.org/10.1007/s10845-018-1411-1

Baratta, A., Cimino, A., Gnoni, M. G., & Longo, F. (2023). Human Robot Collaboration in Industry 4.0: a literature review. Procedia Computer Science, 217, 1887–1895. https://doi.org/10.1016/j.procs.2022.12.389

Baratta, A., Cimino, A., Longo, F., Mirabelli, G., & Nicoletti, L. (2024)a. Task Allocation in Human-Robot Collaboration: A Simulation-based approach to optimize Operator's Productivity and Ergonomics. Procedia Computer Science, 232, 688–697. https://doi.org/10.1016/j.procs.2024.01.068

Baratta, A., Cimino, A., Longo, F., & Nicoletti, L. (2024)b. Digital Twin for Human-Robot Collaboration enhancement in manufacturing systems: literature review and direction for future developments. Computers & Industrial Engineering, 187, 109764. https://doi.org/10.1016/j.cie.2023.109764

Belhadj, I., Aicha, M., & Aifaoui, N. (2022). Product disassembly planning and task allocation based on human and robot collaboration. International Journal on Interactive Design and Manufacturing (IJIDeM), 16(2), 803–819. https://doi.org/10.1007/s12008-022-00908-y

Bellini, E., Bagnoli, F., Caporuscio, M., Damiani, E., Flammini, F., Linkov, I., Lió, P., & Marrone, S. (2021). Resilience learning through self adaptation in digital twins of human-cyber-physical systems. Resilience Learning Through Self Adaptation in Digital Twins of Human-cyber-physical Systems. https://doi.org/10.1109/csr51186.2021.9527913

Bilberg, A., & Malik, A. A. (2019). Digital twin driven human–robot collaborative assembly. CIRP Annals, 68(1), 499–502. https://doi.org/10.1016/j.cirp.2019.04.011

Calzavara, M., Faccio, M., & Granata, I. (2023). Multi-objective task allocation for collaborative robot systems with an Industry 5.0 human-centered perspective. The International Journal of Advanced Manufacturing Technology, 128(1–2), 297–314. https://doi.org/10.1007/s00170-023-11673-x

Casanova, H., Da Silva, R. F., Tanaka, R., Pandey, S., Jethwani, G., Koch, W. F., Albrecht, S., Oeth, J., & Suter, F. (2020). Developing accurate and scalable simulators of production workflow management systems with WRENCH. Future Generation Computer Systems, 112, 162–175. https://doi.org/10.1016/j.future.2020.05.030

Çil, Z. A., Li, Z., Mete, S., & Özceylan, E. (2020). Mathematical model and bee algorithms for mixed-model assembly line balancing problem with physical human–robot collaboration. Applied Soft Computing, 93, 106394. https://doi.org/10.1016/j.asoc.2020.106394

Dobrescu, R., Merezeanu, D., & Mocanu, Ş. (2019). Process simulation platform for virtual manufacturing systems evaluation. Computers in Industry, 104, 131–140. https://doi.org/10.1016/j.compind.2018.09.008

Faccio, M., Granata, I., & Minto, R. (2023). Task allocation model for human-robot collaboration with variable cobot speed. Journal of Intelligent Manufacturing. https://doi.org/10.1007/s10845-023-02073-9

Gjeldum, N., Aljinović, A., Žižić, M. C., & Mladineo, M. (2021). Collaborative robot task allocation on an assembly line using the decision support system. International Journal of Computer Integrated Manufacturing, 35(4–5), 510–526. https://doi.org/10.1080/0951192x.2021.1946856

Guo, D. (2024). Fast scheduling of human-robot teams collaboration on synchronised production-logistics tasks in aircraft assembly. Robotics and Computer-Integrated Manufacturing, 85, 102620. https://doi.org/10.1016/j.rcim.2023.102620

Guo, X., Fan, C., Zhou, M., Liu, S. X., Wang, J., Qin, S., & Tang, Y. (2023). Human–Robot collaborative disassembly line balancing problem with stochastic operation time and a solution via Multi-Objective shuffled frog leaping algorithm. IEEE Transactions on Automation Science and Engineering, 1–12. https://doi.org/10.1109/tase.2023.3296733

Huang, Y., Sheng, B., Luo, R., Lu, Y., Fu, G., & Yin, X. (2024). Solving human-robot collaborative mixed-model two-sided assembly line balancing using multi-objective discrete artificial bee colony algorithm. Computers & Industrial Engineering, 187, 109776. https://doi.org/10.1016/j.cie.2023.109776

Lee, M., Behdad, S., Liang, X., & Zheng, M. (2022). Task allocation and planning for product disassembly with human–robot collaboration. Robotics and Computer-Integrated Manufacturing, 76, 102306. https://doi.org/10.1016/j.rcim.2021.102306

Li, Z., Janardhanan, M. N., & Tang, Q. (2021). Multi-objective migrating bird optimization algorithm for cost-oriented assembly line balancing problem with collaborative robots. Neural Computing and Applications, 33(14), 8575–8596. https://doi.org/10.1007/s00521-020-05610-2

Li, Z., Janardhanan, M. N., Tang, Q., & Zhang, Z. (2023). Models and algorithms for U-shaped assembly line balancing problem with collaborative robots. Soft Computing, 27(14), 9639–9659. https://doi.org/10.1007/s00500-023-08130-y

Liau, Y. Y., & Ryu, K. (2022). Genetic algorithm-based task allocation in multiple modes of human–robot collaboration systems with two cobots. The International Journal of Advanced Manufacturing Technology, 119(11–12), 7291–7309. https://doi.org/10.1007/s00170-022-08670-x

Longo, F., Nicoletti, L., & Padovano, A. (2017). Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. Computers & Industrial Engineering, 113, 144–159. https://doi.org/10.1016/j.cie.2017.09.016

Makrini, I. E., Merckaert, K., De Winter, J., Lefeber, D., & Vanderborght, B. (2019). Task allocation for improved ergonomics in Human-Robot Collaborative Assembly. Interaction Studies, 20(1), 102–133. https://doi.org/10.1075/is.18018.mak

Malik, A. A., & Bilberg, A. (2018). Digital twins of human robot collaboration in a production setting. Procedia Manufacturing, 17, 278–285. https://doi.org/10.1016/j.promfg.2018.10.047

Mao, Z., Wang, Z., Zhang, J., Fang, K., Huang, D., & Sun, Y. (2023). Balancing U-type assembly lines with human–robot collaboration. Computers & Operations Research, 159, 106359. https://doi.org/10.1016/j.cor.2023.106359

Mateus, J. E. C., Claeys, D., Limère, V., Cottyn, J., & Aghezzaf, E. (2020). Base part centered assembly task precedence generation. The International Journal of Advanced Manufacturing Technology, 107(1–2), 607–616. https://doi.org/10.1007/s00170-019-04864-y

Merlo, E., Lamon, E., Fusaro, F., Lorenzini, M., Carfì, A., Fulvio, M., & Ajoudani, A. (2023). An ergonomic role allocation framework for dynamic human–robot collaborative tasks. Journal of Manufacturing Systems, 67, 111–121. https://doi.org/10.1016/j.jmsy.2022.12.011

Messeri, C., Bicchi, A., Zanchettin, A. M., & Rocco, P. (2022). A dynamic task allocation strategy to mitigate the human physical fatigue in collaborative robotics. IEEE Robotics and Automation Letters, 7(2), 2178–2185. https://doi.org/10.1109/lra.2022.3143520

Mura, M. D., & Dini, G. (2019). Designing assembly lines with humans and collaborative robots: A genetic approach. CIRP Annals, 68(1), 1–4. https://doi.org/10.1016/j.cirp.2019.04.006

Mura, M. D., & Dini, G. (2021). Job rotation and human–robot collaboration for enhancing ergonomics in assembly lines by a genetic algorithm. The International Journal of Advanced Manufacturing Technology, 118(9–10), 2901–2914. https://doi.org/10.1007/s00170-021-08068-1

Murgod, T. R., Sundaram, S. M., Mahanthesha, U., & Murugesan, P. (2023). A survey of Digital Twin for Industry 4.0: Benefits, Challenges and opportunities. SN Computer Science, 5(1). https://doi.org/10.1007/s42979-023-02363-2

Nourmohammadi, A., Fathi, M., & Ng, A. H. C. (2022). Balancing and scheduling assembly lines with human-robot collaboration tasks. Computers & Operations Research, 140, 105674. https://doi.org/10.1016/j.cor.2021.105674

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T., Mulrow, C. D., Shamseer, L., Tetzlaff, J., Akl, E. A., Brennan, S., Chou, R., Glanville, J., Grimshaw, J., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E., Mayo-Wilson, E., McDonald, S., . . . Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ, n71. https://doi.org/10.1136/bmj.n71

Ogunsakin, R., Mehandjiev, N., & Marín, C. A. (2023). Towards adaptive digital twins architecture. Computers in Industry, 149, 103920. https://doi.org/10.1016/j.compind.2023.103920

Petzoldt, C., Niermann, D., Maack, E., Sontopski, M., Vur, B., & Freitag, M. (2022). Implementation and evaluation of dynamic task allocation for Human–Robot collaboration in assembly. Applied Sciences, 12(24), 12645. https://doi.org/10.3390/app122412645

Rabbani, M., Behbahan, S. Z. B., & Farrokhi-Asl, H. (2020). The collaboration of Human-Robot in Mixed-Model Four-Sided Assembly Line balancing problem. Journal of Intelligent and Robotic Systems, 100(1), 71–81. https://doi.org/10.1007/s10846-020-01177-1

Rahman, H. F., Janardhanan, M. N., & Ponnambalam, S. G. (2023). Energy aware semi-automatic assembly line balancing problem considering ergonomic risk and uncertain processing time. Expert Systems With Applications, 231, 120737. https://doi.org/10.1016/j.eswa.2023.120737

Şahan, A., Srinivasan, K., Lokesh, M., & Raffik, R. (2023). Role of Cobots over Industrial Robots in Industry 5.0: A Review. 2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA). https://doi.org/10.1109/icaeca56562.2023.10201199

Şahin, M. C., & Tural, M. K. (2023). Robotic stochastic assembly line balancing. Flexible Services and Manufacturing Journal, 35(4), 1076–1115. https://doi.org/10.1007/s10696-023-09494-x

Thoben, K., Wiesner, S., & Wuest, T. (2017). "Industrie 4.0" and Smart Manufacturing – A review of research issues and application examples. International Journal of Automation Technology, 11(1), 4–16. https://doi.org/10.20965/ijat.2017.p0004

Touzani, H., Séguy, N., Hadj-Abdelkader, H., Suárez, R., Rosell, J., Palomo-Avellaneda, L., & Bouchafa, S. (2022). Efficient Industrial Solution for Robotic Task Sequencing Problem With Mutual Collision Avoidance & Cycle Time Optimization. IEEE Robotics and Automation Letters, 7(2), 2597–2604. https://doi.org/10.1109/lra.2022.3142919

Wu, T., Zhang, Z., Zhang, Y., & Zeng, Y. (2023). Modelling and optimisation of two-sided disassembly line balancing problem with human–robot interaction constraints. Expert Systems With Applications, 230, 120589. https://doi.org/10.1016/j.eswa.2023.120589

Zhang, L., Zhou, L., Ren, L., & Laili, Y. (2019). Modeling and simulation in intelligent manufacturing. Computers in Industry, 112, 103123. https://doi.org/10.1016/j.compind.2019.08.004

Zhu, Q., Huang, S., Wang, G., Moghaddam, S. K., Lu, Y., & Yan, Y. (2022). Dynamic reconfiguration optimization of intelligent manufacturing system with human-robot collaboration based on digital twin. Journal of Manufacturing Systems, 65, 330–338. https://doi.org/10.1016/j.jmsy.2022.09.021