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Adaptive Automation Assembly Systems in the Industry 4.0 Era: A Reference Framework and Full–Scale Prototype

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Featured Application: The research study proposed in this paper provides valuable knowledge to support companies and industrial practitioners in the shift from traditional to advanced assembly systems in the new Industry 4.0 era matching current industrial and market features.

Abstract: Industry 4.0 emerged in the last decade as the fourth industrial revolution aiming at reaching greater productivity, digitalization and operational efficiency standard. In this new era, if compared to automated assembly systems, manual assembly systems (MASs) are still characterized by wide flexibility but poor productivity levels. To reach acceptable performances in terms of both productivity and flexibility, higher automation levels are required to increase the skills and capabilities of the human operators with the aim to design next-generation assembly systems having higher levels of adaptivity and collaboration between people and automation/information technology. In the current literature, such systems are called adaptive automation assembly systems (A3Ss). For A3Ss, few design approaches and industrial prototypes are available. This paper, extending a previous contribution by the Authors, expands the lacking research in the field and proposes a general framework guiding toward A3S effective design and validation. The framework is applied to a full-scale prototype, highlighting its features together with the technical- and human-oriented improvements arising from its adoption. Specifically, evidence from this study show a set of benefits from adopting innovative A3Ss in terms of reduction of the assembly cycle time (about 30%) with a consequent increase of the system productivity (about 45%) as well as relevant improvements of ergonomic posture indicators (about 15%). The definition of a general framework for A3S design and validation and the integration of the productivity and ergonomic analysis of such systems are missing in the current literature, representing an element of innovation. Globally, this research paper provides advanced knowledge to guide research, industrial companies and practitioners in switching from traditional to advanced assembly systems in the emerging Industry 4.0 era matching current industrial and market features.

Keywords: self-adaptive assembly system; adaptive automation; reconfigurability; industry 4.0; flexible assembly system; flexibility

Citation: Bortolini, M.; Faccio, M.; Galizia, F.G.; Gamberi, M.; Pilati, F. Adaptive Automation Assembly Systems in the Industry 4.0 Era: A Reference Framework and Full–Scale Prototype. *Appl. Sci.* **2021**, *11*, 1256. https://doi.org/10.3390/app11031256

Academic Editor: Antonella Petrillo
Received: 13 January 2021
Accepted: 26 January 2021
Published: 29 January 2021

1. Introduction

The concept of the industrial revolution is strongly linked to extraordinary growth and change in technology. The first industrial revolution (1750–1870) caused an increase in the application of science to industry and led to the rise of mechanized production. The second revolution (1870–1970) was caused by electrical motors powered by electricity and led to the rise of mass production and large-scale machine tools manufacturing. The third revolution (1970–2011) was characterized by the deployment of Programmable Logic Controllers (PLC) and Information and Communication Technology (ICT) derived by digital signals and led to production automation and human-controlled manufacturing. Finally, the ongoing fourth industrial revolution (2011-today), known as Industry 4.0, lays on autonomous manufacturing and connected businesses [1]. In particular, Industry 4.0 includes nine enabling technologies to support the implementation of the paradigm in industry, as in Table 1 [2].

Table 1. Industry 4.0 enabling technologies.

Id.	Enabling Technology	Description
1	Advanced Manufacturing Solutions	Autonomous, cooperating industrial robots Numerous integrated sensors and standardized interfaces
2	Additive Manufacturing	3D printing, particularly for spare parts and prototypes Decentralized 3D facilities to reduce transport distances and inventory
3	Augmented Reality	Augmented reality for maintenance, logistics Display of supporting information, e.g., through glasses
4	Simulation	Simulation of value networks Optimization based on real-time data from intelligent systems
5	Horizontal/Vertical Integration	Cross-company data integration based on data transfer standards Precondition for a fully automated value chain
6	Industrial Internet	Network of machines and products Multidirectional communication between networked objects
7	Cloud	Management of huge data volumes in open systems Real-time communication for production systems
8	Cyber-security	Operation in networks and open systems High level of networking between intelligent machines, products and systems
9	Big Data and Analytics	Full evaluation of available data (e.g., from ERP and machine data) Real-time decision-making support and optimization

In the current production context, factors as efficiency, flexibility and responsiveness to the dynamic market demand are crucial for the survival of industrial companies [1–4]. Modern production systems have to face with emerging factors such as shorter product lifecycles, the mass-customization and personalization and the reduction of the delivery time to the customers [5,6]. The upcoming fourth industrial revolution can play a crucial role in managing such complexity, representing the global transformation of the overall industrial production through the integration of Internet of Things (IoT) and Information and Communication Technologies (ICT) with traditional production processes [7,8]. In this context, embedded systems, semantic machine-to-machine communications and Cyber–Physical System (CPS) technologies connect the virtual space to the physical world [9].

Despite the increased levels of digitization and automation led by Industry 4.0, assembly systems are still based on manual labor because of several human skills, i.e., cognitive ability and problem-solving, are still irreplaceable [10–12]. However, despite such flexibility, manual assembly systems (MASs) lack in terms of:

- Productivity; which is low compared to fully automated systems [13]. This aspect is crucial in regions characterized by high labor costs, i.e., the western countries, for its impact on the product full cost and market price [14];
- Accuracy of the performed tasks; the ability to perform continuously the same assembly tasks taking the same time and using the same tools is low in manual systems because of the variability of human nature [15,16];
- Ergonomic work conditions; such factors, if not optimized properly, can further reduce productivity causing musculoskeletal disorders (MSDs) and other related factors, e.g., absenteeism, stress.

In manual assembly, activities to be performed are usually characterized by several phases, like the picking of the assembly components, walking within the industrial layout, the performance of the assembly tasks, etc. Past studies by Wild [17], Finnsgård et al. [18] and Finnsgård and Wänström [19] determined that picking activities cover a wide percentage of the cycle time, usually more than 50% of the global assembly time. Proper execution of these activities strongly influences the time needed to complete the whole assembly process and the human operator work conditions, affecting productivity and ergonomic performances [9]. To increase these performances maintaining flexibility, next-generation MASs are asked to introduce higher automation and collaboration levels to increase the skills of the operators providing the manual work [12,20]. This issue remarks the need to designing reconfigurable, self-adaptable and collaborative assembly systems through digital technologies and intelligent automation [21–23] to accommodate the assembly of a wider range of product variants, characterized by different features, i.e., size, volume, work cycle, and the features of the human operators performing the assembly tasks, i.e., anthropometric measurements. All these aspects stress the compelling urgency to explore and determine human and technological needs of the assembly systems of the future to design and spread them into the industry. Such systems are emerging in the current literature as adaptive automation assembly systems (A3Ss). Although some qualitative studies attempted to conceptualize such systems introducing their key features and identifying the main system requirements [10,12,22], so far, real industry-oriented framework, A3S design approaches and prototypes, and numerical analysis to a benchmark such innovative systems toward traditional ones are still missing and expected. In this scenario, this paper, extending a previous study proposed by Bortolini et al. [20], presents a general framework guiding toward the effective design and validation of A3Ss, which can efficiently cope with dynamic production conditions, including the worker variability. The proposed framework is then applied to a full-scale prototypal A3S, named Self-Adaptive Smart Assembly System (SASAS), describing its features together with the productivity and ergonomic improvements arising from its adoption. The definition of a general framework for A3S design and validation and the integration of the productivity and ergonomic analysis of such systems are missing in the current literature, representing a relevant element of innovation.

Starting from this background, this paper is structured as follows. Section 2 reviews the relevant literature in the field of advanced assembly, while Section 3 illustrates the general framework for the A3S design and validation. The application of the proposed framework to a prototypal A3S is in Section 4, while a lab experimental analysis on the assembly prototype, proving its benefits in terms of productivity and ergonomics, is in Section 5. Section 6 illustrates a multi-scenario analysis to generally quantify the benefits achievable by introducing modern A3Ss in industrial companies while, finally, Section 7 concludes this paper with some remarks and future opportunities for research.

2. Literature Review

Modern trends such as mass customization, higher product variability, reduced product life cycles and variable production batches require production systems to be designed for rapid reconfiguration and self-adaptation in response to disruptions, in terms of either product changes or changes in other operational parameters [24–28]. Research in the area proposes, among others, reconfigurable manufacturing and assembly systems with 'plug and produce' technologies [29], holonic manufacturing and evolvable collaborative manufacturing and assembly systems [23,29–31]. In this field, methods aiding the design and management of these emerging systems are needed, to allow a reconfiguration guided by humans or by an agent control layer [25]. Suitable architectures are needed to be developed to best manage the integration among the huge amount of data collected by dedicated sensors from the shop floor, their proper analysis and elaboration and the feedback to provide to the physical entities. In this context, CPSs act to collect this process into a flexible architecture able to assist industrial practitioners in performing a huge number of production tasks. Preventive and corrective decisions work as feedback from the cyber to the physical world to make the devices under control self-reconfigurable and self-adaptive [32,33].

In the modern context of Industry 4.0, MASs still play a crucial role because of the flexibility they offer in performing model changeovers in a fast and easy way, in processing multiple product variants and models simultaneously and in being responsive to changes in part design [15]. To complement such flexibility with greater levels of productivity, the human and the automation factors need to be merged to design responsive and efficient assembly systems. In this field, Krüger et al. [34] stress as changeability and flexibility of modern assembly processes ask for strong cooperation between the human operator and the automated assembly system. They propose a survey about human-machine cooperation in assembly systems, mapping the available technologies supporting the cooperation. Fast-Berglund et al. [35] explore the relevant features of Industry 4.0 in the assembly field and perform a literature review of the most relevant research contributions. The selected papers are classified according to the topic they address is relevant to the human perspective, the automation perspective or the integrated human-automation perspective. The findings of this survey show the need to better understanding the requirements of the human and technology components to best design, manage and spread into the industry, such as future assembly systems. The studies proposed by Bortolini et al. [9] and Cohen et al. [36] study the impact of Industry 4.0 elements on the design and management of advanced assembly systems. Bortolini et al. [9] explore the evolution of the industrial scenario during the last three centuries and describe the main technological innovations that enable the digitalization of the assembly process. Cohen et al. [36] introduce a methodological framework to apply Industry 4.0 technologies and the reconfigurability attribute in existing production, i.e., manufacturing and assembly, systems as well as in designing novel systems presenting an industrial case of a refrigerator manufacturer. Sanderson et al. [25] stress the need for the definition of behavioral approaches supporting the design of evolvable assembly systems, which rise as a particular type of self-adaptive reconfigurable assembly systems. In particular, the Authors propose an innovative design process for such systems, exploring how the system hardware structure and its behavior are related to the system functions and demonstrate the validity of their methodology through a real case study in the aerospace industry. Fletcher et al. [12] state that future manufacturing and assembly systems should be designed and realized to reach economic and social sustainability within volatile and dynamic conditions and for adaptive utilization of human workers' personal skills to guarantee high productivity targets and job satisfaction. To reach this goal, the Authors perform a deep survey to determine the main requirements needed to create this design framework for next-generation integrated human-automation assembly systems. Faccio et al. [23] stress the crucial role of collaboration in modern assembly, comparing the performances of traditional assembly systems with that of collaborative systems. Results prove that collaboration acts as a relevant means to reduce the assembly cycle time, increasing productivity.

The literature review shows the existence of a relevant number of theoretical studies on A3Ss but a lack of design methodologies supporting their introduction in the industry. To fill this gap, this study introduces a methodological framework supporting the design and validation of A3Ss as innovative solutions joining the main benefits of both automated and manual systems. Therefore, the engineering and testing of a prototypal full-scale A3S is proposed, highlighting its benefits compared to traditional solutions.

3. New Methodological Framework

Figure 1 shows the methodological framework aiming to guide toward the effective design and validation of A3Ss, which are rising as innovative systems combining the strengths and overcoming the weaknesses of both automated systems and MASs. The framework consists of three main sections: (1) automated assembly systems, on the left, (2) MASs, on the right, and (3) A3Ss, in the central part, as a joint paradigm.

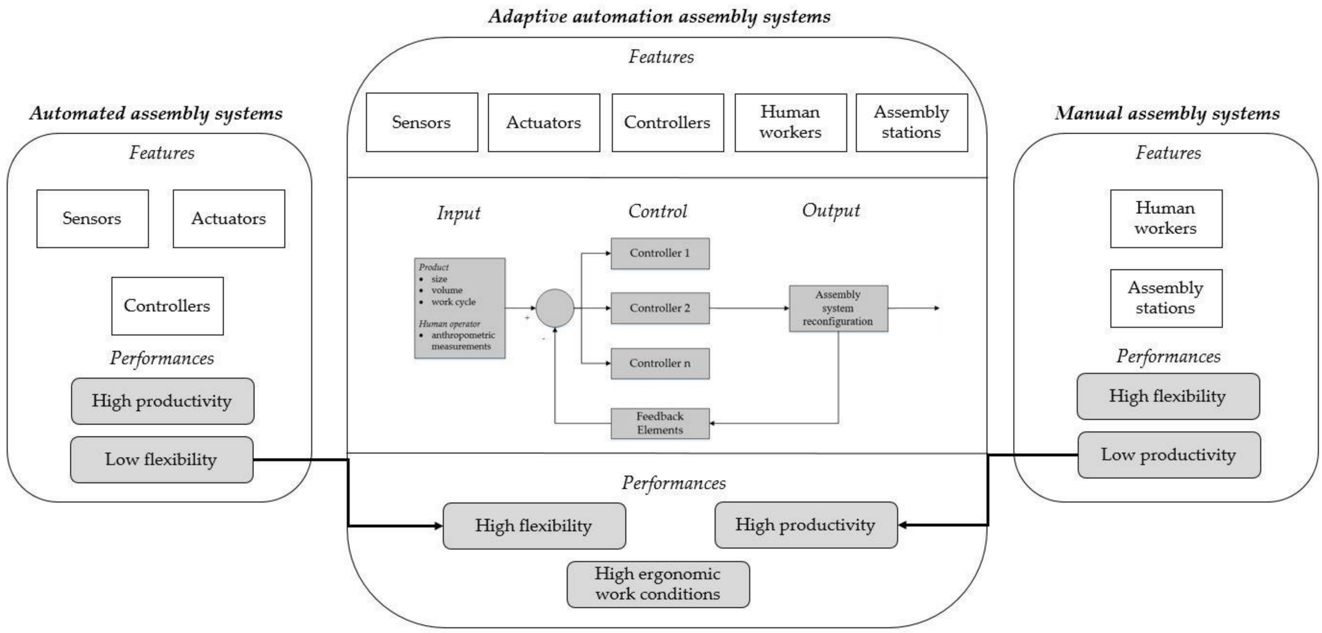


Figure 1. New methodological framework for A3S design and management.

In automated assembly systems, controllers, sensors and actuators are interconnected to enable monitoring, control and collaboration and to exchange operational information [37]. The literature classifies these systems in dedicated and flexible assembly systems (FASs). The former is suitable for the production of wide batch sizes and their implementation typically leads to high performances in terms of productivity but low performances in terms of flexibility. To slightly increase flexibility, past literature proposes the FASs characterized by programmable manipulators and by flexible feeder subsystems. However, in such a configuration, the components change largely influences the automation process, causing the need for additional investments and rising management costs [15]. If high flexibility is required, MASs composed of human workers and manual assembly stations can be adopted obtaining a significant decrease in productivity [15]. In addition, unlike the automated systems, the performances of the workers are strongly affected by ergonomic issues that, if not managed properly, can further decrease the productivity levels causing MSDs and absenteeism [38]. In particular, critical conditions occur in assembly systems, e.g., a considerable level of stress, uncomfortable postures and the performance of repetitive movements etc. These conditions lead to the insurgency of work-related MSDs [39]. For these reasons, a strong connection between MASs and ergonomics exists, both in theory and in practice, which needs to be effectively managed.

Emerging factors such as variable market demand and batches, flexibility and increased product customization and personalization characterize the upcoming Industry 4.0 era, forcing industrial companies to reshape their practices in process and product design and management [2]. In this context, production systems reaching significant levels of both productivity and flexibility are a plus. A3Ss are an innovative class of MASs including higher automation and collaboration levels to improve and increase the capabilities and skills of the workers who perform the manual work [12]. Humans still represent one of the most flexible components of assembly and manufacturing systems and new manufacturing and assembly systems are designed not to remove but to support and guide them by implementing new technologies, enhancing their skills and overcoming any limitation [40,41]. A3Ss rise as integrated systems involving unheard requirements of socio-technical integration and reconfigurability in which hardware, i.e., machines, controllers, sensors and actuators, and the human contribution coexist to benefit of each other's strengths. These goals are achieved thanks to the adaptive and collaborative features of A3Ss, which allow the assembly system to perform a real-time reconfiguration of its hardware structure, partially or totally in parallel to the performance of the assembly tasks by the human worker, according to product input data, e.g., work cycle, dimension, and human workers input data, e.g., anthropometric measurements. Such a real-time reconfiguration together with the human contribution allows reaching good performances in terms of productivity and flexibility as well as improvements in the ergonomic work conditions. The next Section 4 exemplifies these concepts introducing a prototypal full-scale A3S, i.e., SASAS.

4. A Full-Scale Prototypal Adaptive Automation Assembly System

This section presents an integrated hardware/software full-scale prototypal A3S, called SASAS. Three parts are detailed; (a) the hardware prototype, taken from [20], (b) the graphic user interface (GUI), built through the Matlab® software, to manage the SASAS real-time reconfiguration and (c) the motion analysis system to track the human operator and to monitor its productivity and ergonomic performances.

4.1. Hardware Prototype

As stated in Section 2, the current literature is characterized by a lack of design methodologies supporting the introduction of A3Ss in modern industrial companies. To fill this gap, this section proposes a prototypal A3S, called SASAS, describing the main benefits, i.e., increased flexibility and productivity standards, in comparison to the assembly applications currently diffused and applied in industry. Next, Figures 2 and 3 show the Computer Aided Design (CAD) model, the 3D and the real image of the full-scale assembly workstation.

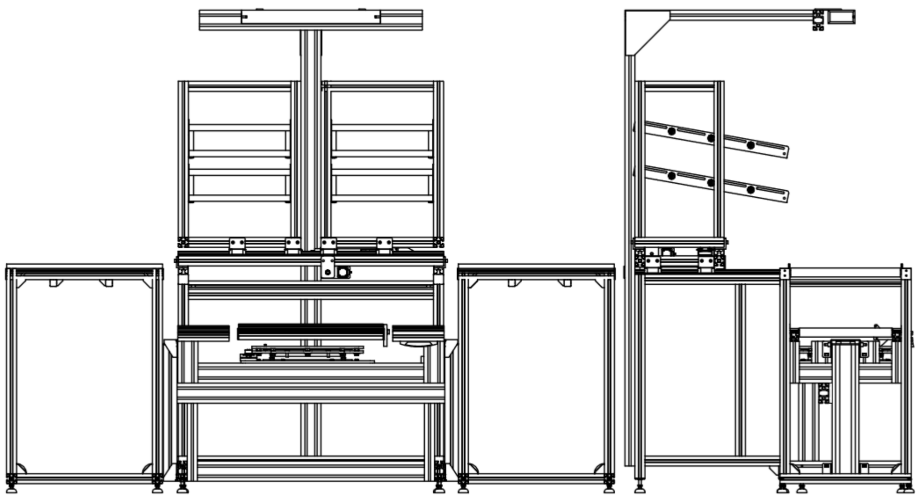


Figure 2. Front and lateral Computer Aided Design (CAD) model of the Self-Adaptive Smart Assembly System (SASAS) prototype [20].

The components required to assemble the product variants are located in a fast-picking zone (1) composed of two main modules, which are able to flow along the two Cartesian axes, performing symmetrical lateral extension (LE in Figure 3) and moving toward the human worker (FE in Figure 3) to provide support and ease the picking phase. This element is a relevant novelty because nowadays in industry, the assembly components are usually stored behind the human worker, producing a significant walking time, repetitive movements and uncomfortable postures, responsible for MSDs and stress. This design overcomes the industrial practice allowing significantly reducing the movements made by the human workers and, as consequence, reducing the overall picking time. In addition, the fast-picking zone, together with its movements along the two Cartesian axes, i.e., LE and FE, avoid wrong postures increasing the operator's comfort and productivity.

Furthermore, the SASAS is characterized by three-roller conveyors, two lateral allowing the product flow (3) and one centrally located devoted to the performance of the assembly tasks by the human worker (4), which can translate vertically (VE in Figure 3).

When the piece is in (4), the central roller conveyor is locked by a set of spring-loaded components and an intelligent mechanism allows its rotation. The prototype enables setting the height of the main roller conveyor according to the anthropometric measurements of the worker, i.e., height, and to the task to perform within the assembly process, e.g., in case of operations to perform on the upper surface of a medium-large size product, the roller conveyor reaches an acceptable position for the operator.

Figure 3. 3D layout and real picture of the SASAS prototype: 1. Fast-picking zone for the storage of the assembly parts; 2. Extendable supports of the main roller conveyor; 3. Lateral roller conveyor; 4. Main roller conveyor (**left**), and a real image of the assembly prototype (**right**). Motion axes: Lateral Extension (LE), Frontal Extension (FE), Vertical Extension (VE).

4.2. Real-Time Control and Reconfiguration

The control design represents another relevant aspect to best manage, largely explored in the last years by the scientific community [42,43]. In this study, the SASAS control and reconfiguration are real-time managed by the Programmable Logic Controller (PLC), i.e., Bosch Rexroth XM type, governed by Bosch software IndraWorks Engineering. To allow the human workers to reconfigure in real-time the assembly system structure according to the product characteristic, the work cycle and their anthropometric measurements, a GUI is developed (Figure 4).

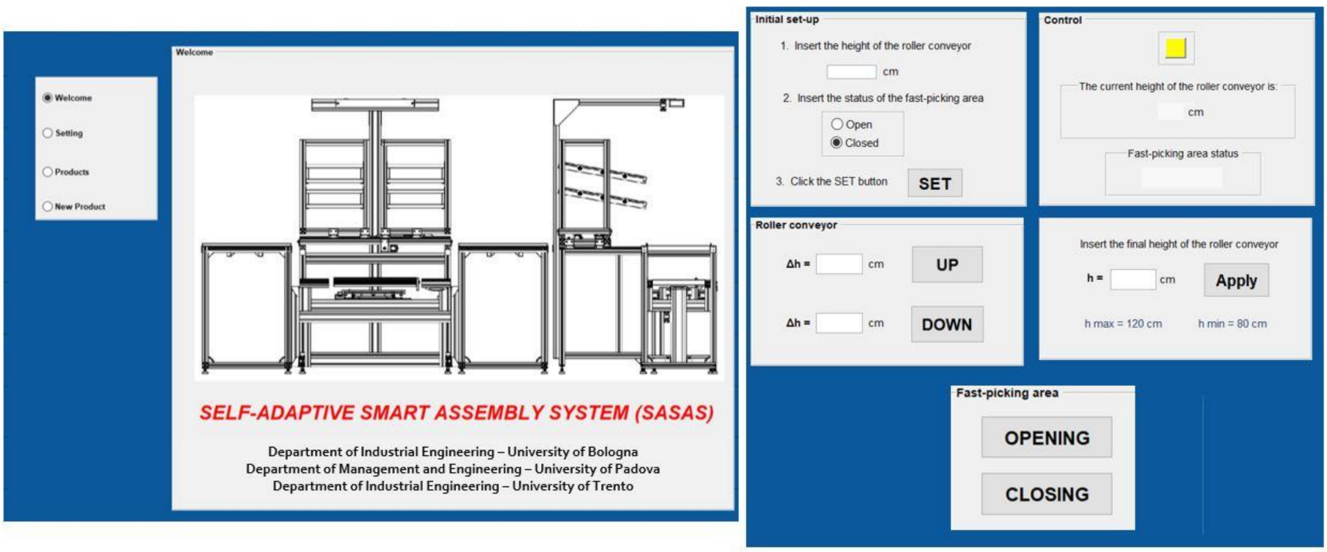
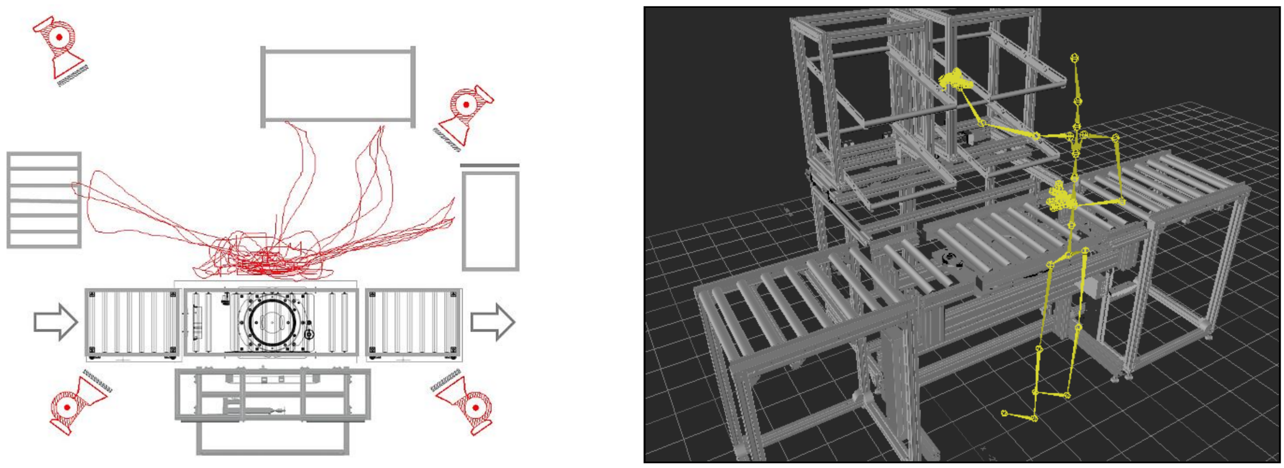


Figure 4. Graphic user interface (GUI) for the real-time control and reconfiguration.

In detail, the GUI is built through the Graphic User Interface Development Environment (GUIDE) Matlab® toolbox and it guides the human workers in the real-time system self-adaptability and reconfiguration, containing data and information about the work cycles of the products realized by the industrial company and linking the assembly tasks to specific reconfiguration movements of the assembly system structure. In this context, the SASAS acts as a collaborative system: the reconfiguration of the hardware system structure is performed partially or totally in parallel to the performance of the assembly tasks by the human worker, guaranteeing savings in terms of reduced cycle time and increased productivity. In this way, this paper overcomes the main limitations of the assembly prototype presented in [20], in which the system reconfiguration was performed manually by the human operator, necessarily increasing the product cycle time. Moreover, in the proposed GUI, the inclusion of new products is possible guaranteeing flexibility. This feature is relevant because the market asks for a wide number of customized variants. The developed GUI helps the workers in managing modern variety allowing them to update or add easily new product work cycles, choosing the right SASAS movements for reconfiguration.

4.3. Motion Analysis System for Productive and Ergonomic Evaluation

To track the human operator inside the industrial working environment and to monitor its performances, a motion analysis system is added [44]. It aims at analyzing the human work providing a detailed report, e.g., time and 3D space, from the production and ergonomic viewpoint. The applied technology is a human marker-less motion capture (MOCAP) system, digitalizing the operator body during his work and placing it into the working space, as in Figure 5.



(a) (b)

Figure 5. Motion analysis system: (**a**) architecture of the system with cameras positioned; (**b**) 3D digital environment with the human operator.

A Wi-Fi network characterized by four depth cameras connected to dedicated laptops, i.e., a master and three slaves, makes the hardware. The depth cameras adopted to develop the motion analysis system are Microsoft Kinect v.2™, already successfully employed to track human workers in industrial applications, characterized by a color RGB sensor and an IR depth sensor. The software architecture to drive the dynamic evaluation of the assembly operator is designed to provide the human body digitalization by using the network of depth cameras and it is developed in Matlab® environment through the Image Acquisition toolbox.

Body digitalization is based on recording the movements of the skeleton collecting the 3-D position of the human body joints over time. The required information to evaluate the assembly process is the set of body joints and their positions, which represent the base to analyze the performances, i.e., productive and ergonomic, of the assembly worker as well as to perform the dynamic space analysis. In particular, the productive perspective is evaluated by performing a dynamic analysis of the human worker movements in the working area, providing information as the task execution time, hands and full-body movements. The ergonomic assessment is performed computing ergonomic indices internationally defined, as the Rapid Entire Body Assessment (REBA) index. REBA analyses the human worker postures assessing the position of the main body parts and the angle of the joints representing the human skeleton [45–47].

To summarize, the proposed integrated hardware/software methodology is able to identify product features and human workers' anthropometric measurements, and consequently, reconfigure the A3S hardware structure to match such data. Among the potential limitations of the proposed integrated hardware/software full-scale prototypal A3S, surely the degree of product complexity affects its technical performances. Specifically, such a prototype achieves high-performance targets for the assembly of small and medium-sized products, i.e., gross volume up to 1.5 m^3. However, such a limitation is not in contrast with the modern Industry 4.0 market trend, asking for small/medium items with dynamic demand.

5. Experimental Analysis

This analysis aims at testing the performances of the SASAS prototype in terms of productivity and ergonomic work conditions in a realistic environment, focusing on the assembly process of a horizontal multistage centrifugal electric pump. Figure 6 shows a picture of the reference pump. The product, after the assembly phase, must be inserted into a carter.

Figure 6. Reference product used for the lab experimental field-test.

The developed experimental analysis compares two main assembly configurations, named as in the following:

- Configuration #1: traditional MAS;
- Configuration #2: SASAS prototype, including Configuration #2.1 (SASAS prototype with manual reconfiguration) and Configuration #2.2 (SASAS prototype with automatic reconfiguration).

In Configuration #1, the assembly system works as a fixed, i.e., rigid, workstation, not using the key attribute of self-adaptability to the part and human operator features. In such a configuration, the fast-picking area is as in Figure 3 (left) and the central conveyor is set to a height equal to 0.95 m from the floor. In addition, the components are placed on shelving behind the assembly prototype, at a distance of 2 m, and the additional tools, e.g., screwdrivers, screws, etc., are placed in the fast-picking zone of the SASAS. In Configuration #2, the adaptivity feature is used, making the system able to manually, i.e., Configuration #2.1, and automatically, i.e., Configuration #2.2, reconfiguring in real-time its structure according to the work cycle of the product and to the anthropometric measurements of the human worker performing the assembly process.

The analysis assesses the cycle time, T_c, i.e., the time required to complete the whole assembly process, the system average productivity, $Q = 1/T_c$, and tracking the REBA ergonomic index. Many tests are performed to collect such performance parameters. In each configuration, the minimum number of tests, n, to get statistical reliability is determined using the formula presented in [48]. Values of parameter n equal to 19.07 in Configuration #1, to 16.65 in Configuration #2.1 and to 56.62 in Configuration #2.2 guarantee a statistical significance. A global number of 60 tests per each configuration is performed, getting the average cycle time in Table 2.

Table 2. Cycle time [s/pc] results for the three analyzed configurations.

	Average Cycle Time	Gap toward Configuration #1
Configuration #1	93.6	-
Configuration #2.1	69.9	−25.3%
Configuration #2.2	57.5	−38.6%

The average system productivity for the two configurations is in Table 3.

Table 3. Average productivity [pcs/h].

	Average Productivity	Gap toward Configuration #1
Configuration #1	38.5	-
Configuration #2.1	51.5	+33.9%
Configuration #2.2	62.6	+62.8%

Results confirm the positive impact coming from the SASAS use. In particular, compared to Configuration #1, i.e., traditional assembly, through the system automatic reconfiguration, i.e., Configuration #2.2, the cycle time decreases by 38.6%, while the productivity increases by 62.8%.

To stress the key role played by the collaborative feature in cycle time reduction and productivity increase, a focus on the assembly process of the centrifugal electric pump is proposed, highlighting the specific assembly and reconfiguration tasks in both Configuration #2.1 and #2.2 (Table 4). The most relevant results are in Table 5.

Table 4. Centrifugal electric pump assembly and reconfiguration tasks (Configuration #2.1 and #2.2).

Tasks	Assembly /Reconfiguration	Task Description	Manual Reconfiguration	Automatic Reconfiguration (Collaboration Effect)
			Duration [s]	
#1	Assembly	Pump crankcase picking and drop-off on the central roller conveyor	10	10
	Reconfiguration	Opening of the fast-picking area	5.9	0
#2	Assembly	Picking of the pump rotor from the fast-picking area and assembly	11	11
#3	Assembly	Picking of the seal housing disk from the fast-picking area and assembly	12	12
	Reconfiguration	Closing of the fast-picking area	5.9	0
#4	Assembly	Screwing operation on the upper surface of the pump	9	9
	Reconfiguration	Raising of the central roller conveyor	4.05	3.75
#5	Assembly	Screwing operation on the lower surface of the pump	8	8
	Reconfiguration	Lowering of the central roller conveyor (0.95 m from the floor)	4.05	3.75

Table 5. Cycle time [s/pc] decomposition (assembly and reconfiguration) in Configuration #2.1 and #2.2.

	Configuration #2.1	**Configuration #2.2**
Assembly time	50	50
Reconfiguration time	19.9	7.5
Cycle time	69.9	57.5

Data in Tables 4 and 5 show that the collaborative feature of the SASAS allows getting further improvements in terms of cycle time and productivity moving from Configuration #2.1 to Configuration #2.2. In detail, in Configuration #2.1 the system reconfigurations are performed manually by the human workers so that they totally contribute to the final cycle time. In Configuration #2.2, the reconfigurations are performed partially or totally in parallel to the execution of the assembly tasks by the human worker, according to the specific features of the assembly tasks. The gap between the assembly cycle time in Configuration #2.1 and Configuration #2.2 is about 20%. Next Figure 7 shows a Gantt chart for the assembly process execution in such two configurations.

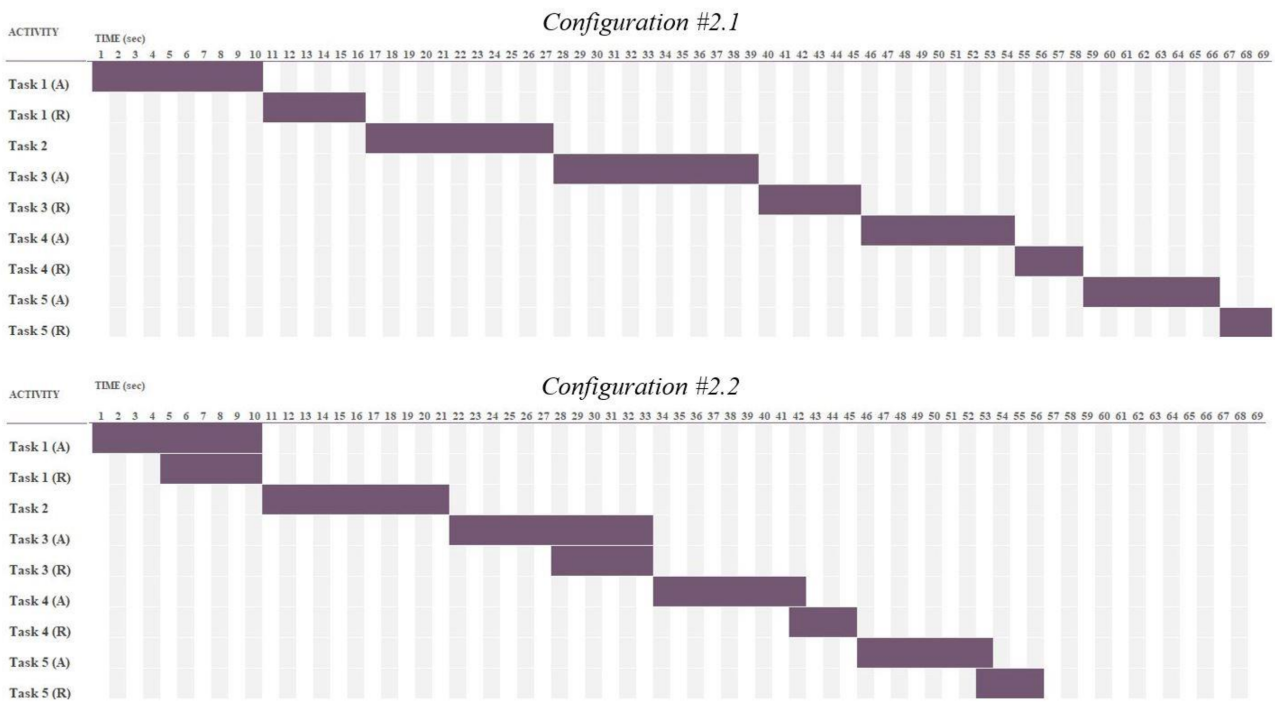


Figure 7. Gantt chart for Configuration #2.1 and Configuration #2.2. (A = Assembly; R = reconfiguration).

Finally, a collaboration index (CI) is proposed to quantify the portion of the cycle time in which the system and the human operator work together (Equation (1)).

$$\mathrm{CI} = \frac{\text{System/man co} - \text{working time}}{\text{Cycle time}}\ [\%] \quad (1)$$

The numerical value of CI is up to 0 for Configuration #2.1 and to 21.6% for Configuration #2.2.

Besides these times saving and productivity increases, an ergonomic analysis is performed assessing the REBA index for each of the 60 tests for the three configurations. Table 6 illustrates the average results.

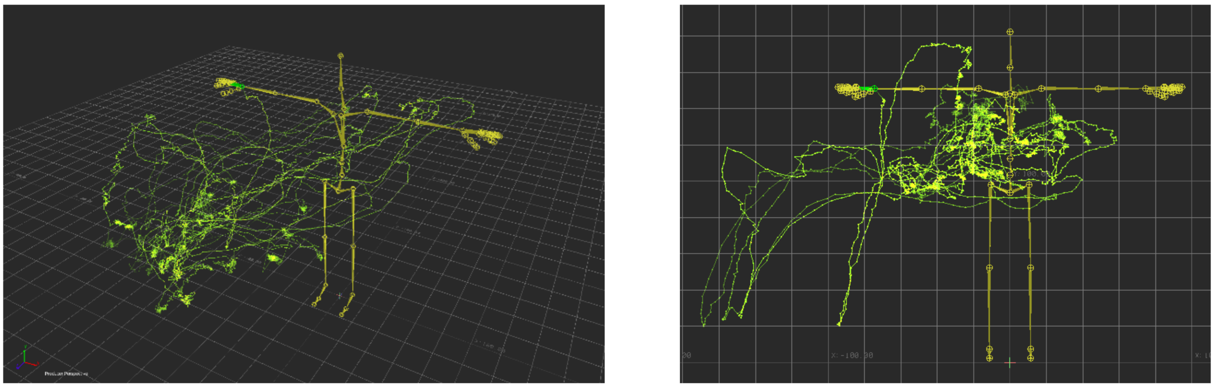
Table 6. Experimental campaign results for the three analyzed configurations, Rapid Entire Body Assessment (REBA) index [pts].

	Average REBA Index	Exposure Risk Level
Configuration #1	4.16	Medium
Configuration #2.1	3.53	Low
Configuration #2.2	3.53	Low

The average REBA index for Configuration #1 is 4.16 leading to a medium risk level according to the REBA scale, while in Configuration #2.1 and in Configuration #2.2 the REBA index is 3.53, meaning a low-risk level. The ergonomic improvement is about 15%. A3Ss may be a key opportunity for industrial companies to reduce the risks of work-related MSDs.

Finally, behind such technical and ergonomic improvements, the use of the SASAS prototype allows reducing the picking time and the operator movements toward standard rigid assembly systems. To prove these benefits, a dynamic space analysis is performed through the motion analysis system described in Section 4.3, building the 2D and 3D spaghetti charts, which trace the traveled distances during the execution of the assembly task. Figure 8 shows the analysis for Configuration #1 and Configuration #2. Configuration #2 integrates the previous #2.1 and #2.2 because, in such two configurations, the spaghetti charts are identical.

(**a**) Traditional Assembly System, Configuration #1



(**b**) Smart Adaptive Smart Assembly System (SASAS), Configuration #2

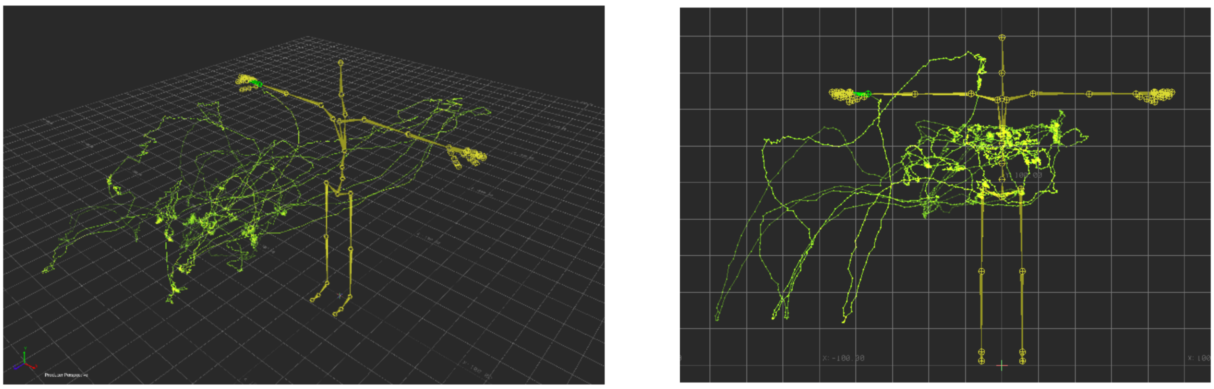
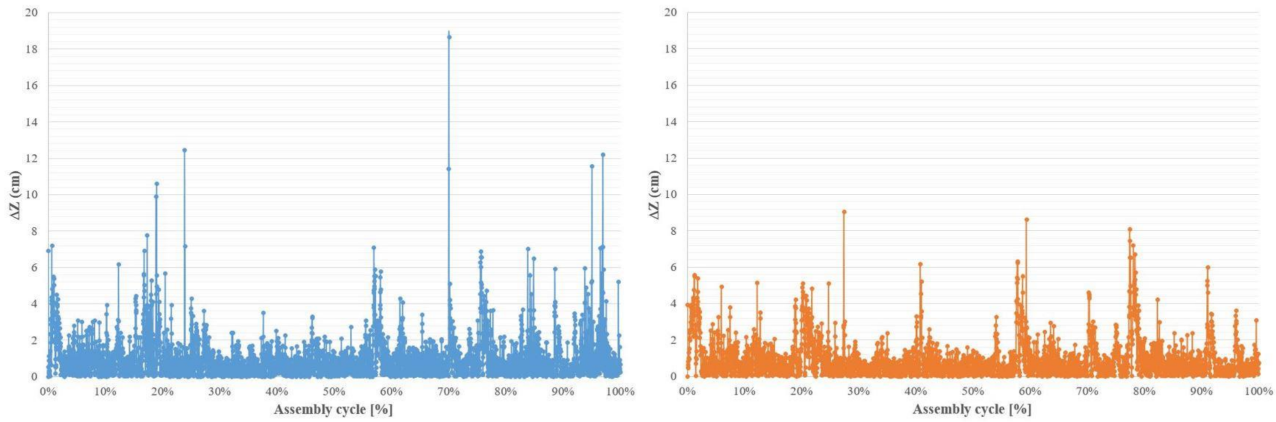


Figure 8. Spaghetti chart for (**a**) Configuration #1 and (**b**) Configuration #2.

The average traveled distance per test, i.e., per each product, is up to 28.0 m in Configuration #1 and 18.5 m in Configuration #2 getting a saving of 33.9%. This result is due to the low access to the shelving behind the human worker. Furthermore, focusing on the right-hand movements, i.e., right-handed operator, the MOCAP system reveals cumulative movements along the z-axis of about 38.0 m per test in Configuration #1 and of about 26.4 m per test in Configuration #2, getting a saving of about 30.5%. Figure 9 shows the variation per frame along the z-axis of the operator's right hand, i.e., 33 ms/frame, while using the traditional assembly system (left) and the A3S (right).



(**a**) (**b**)

Figure 9. Variations along the z-axis of the right hand for (**a**) Configuration #1 and (**b**) Configuration #2.

Figure 9 shows the existence of wider movements using the traditional assembly system, up to 19 cm, while the use of the A3S prototype allows reductions, i.e., most of the movements do not overcome 5 cm with a maximum value of about 9.5 cm.

Globally, the prototype experimental analysis exemplifies, for this reference industrial scenario, the convenience coming from the adoption of the new A3S paradigm in terms of productivity increase, cycle time reduction and ergonomic level improvement.

Next, Section 6 illustrates a final multi-scenario analysis to generally prove and quantify the benefits, in terms of cycle time, achievable by introducing the new A3Ss in industrial companies.

6. Multi-Scenario Analysis

In this section a general multi-scenario analysis is developed, considering the effect of the automatic reconfiguration of a smart self-adaptive prototype (as in Configuration #2.2) toward the manual reconfiguration (as in Configuration #2.1). The aim of this analysis is to prove the potential cycle time saving achievable by implementing such systems, as described in the proposed framework in Section 3. The parameters included in the analysis are in the following, while their range of variation and/or specific values are in Table 7.

Table 7. Range of variation of the input parameters.

	Values	Measurement Unit
MT	[60: 60: 1800]	Sec/pc
ART	[1 5 10 15 20]	Sec/reconfiguration
RN	[0:1:100]	integer
M%	[0:25:100]	%

Input

- MT: (mounting time) of the assembly process [sec/pc]
- ART: (average reconfiguration time) for a single reconfiguration task of the SASAS [sec/reconfiguration]

- RN: (number of reconfigurations) during the cycle time [# reconfigurations/cycle time]
- M%: (average masked time percentage) of the SASAS reconfiguration during the assembly tasks performed by the operator [%]. For SASAS prototype with manual reconfiguration M% = 0, while, in the case of automatic reconfiguration and complete collaboration, M% = 100.

The numerical analysis assesses, as a function of the input parameters, the following output.
Output

- CTmr: (cycle time with manual reconfiguration) of the SASAS prototype (as in Configuration #2.1) [sec/pc] evaluated as:

$$\text{CTmr} = \text{MT} + \text{ART}\cdot\text{RN} \tag{2}$$

- CTar: (cycle time with automatic reconfiguration) of the SASAS prototype (as in Configuration #2.2) [sec/pc] evaluated as:

$$\text{CTar} = \text{MT} + \text{ART}\cdot\text{RN}\cdot(100 - \text{M}\%) \tag{3}$$

- DELTA: (gap percentage of the cycle time between the two configurations) of the SASAS prototype evaluated as in Equation (4).

$$\text{DELTA} = \frac{\text{CTmr} - \text{CTar}}{\text{CTar}}\,[\%] \tag{4}$$

To perform the multi-scenario analysis, values of MT between 60 and 1800 sec/pc (step equal to 60 s) are considered. The number of reconfiguration varies from 0 to 100 (step equal to 1) and each reconfiguration takes from 1 to 20 s (step equal to 5 s). Finally, the average masked time percentage ranges from 0 to 100% (step equal to 25%). The main results are summarized in Figures 10 and 11.

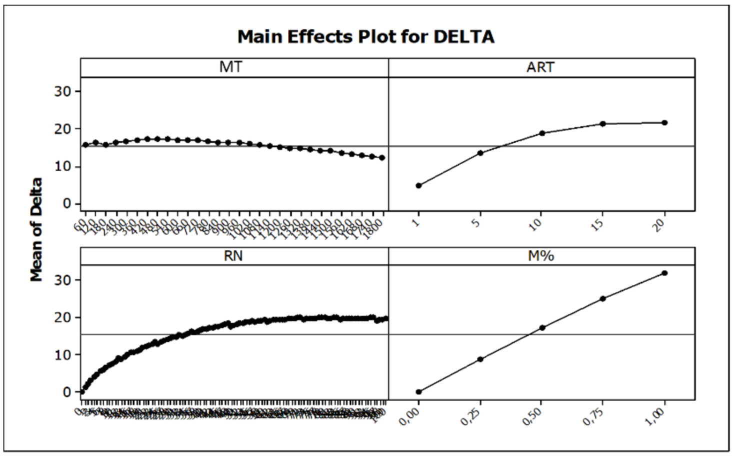


Figure 10. Main effect plot of gap percentage of the cycle time between the two configurations (DELTA) versus mounting time (MT), average reconfiguration time (ART), number of reconfigurations (RN), average masked time percentage (M%).

Figure 10 shows the ANOVA analysis of the input values versus DELTA. The main effect plot demonstrates that the mounting time MT does not affect the result. On the other hand, it shows a positive influence of ART and RN with a less than linear behavior, while M% has a direct positive linear influence. The average cycle time reduction moving from manual to automatic reconfiguration ranges from 0 to more than 20%.

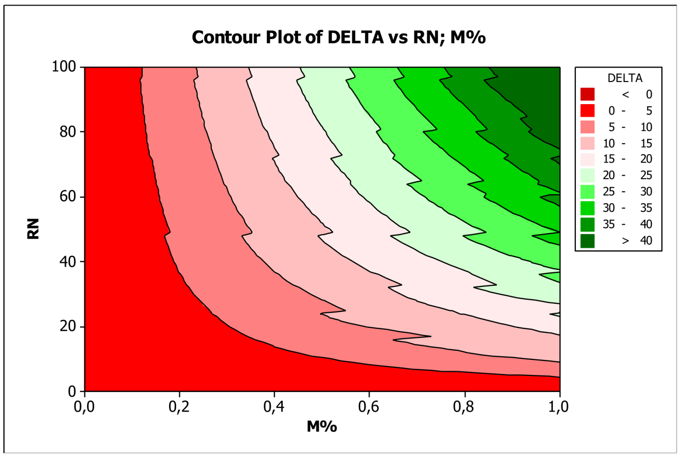


Figure 11. DELTA trend toward M% and RN.

Considering ART = 5 s, as in the experimental analysis of the proposed SASAS prototype, Figure 11 shows the DELTA trend versus M% and RN for the considered MT range of variation. The contour plot in Figure 11 shows a hyperbolic trend according to the two input parameters, with a potential saving that can reach 40% of the entire cycle time.

Considering more than 75.000 scenarios, this multi-scenario analysis generally tests the concept of A3Ss with automatic reconfiguration, showing the potential benefits in terms of cycle time-saving.

7. Conclusions and Future Research

The last decade is characterized by the advent of the 4th industrial revolution, known as Industry 4.0, which plays a crucial role in managing modern production complexity. However, despite the increased levels of digitization and automation led by Industry 4.0, assembly systems are still based on manual labor because of key irreplaceable human abilities. To increase the productivity and the ergonomic performances of manual assembly systems (MASs), maintaining flexibility, next-generation MASs are required to introduce higher automation and collaboration levels to increase the capabilities and skills of the operators. This issue brings the need to designing adaptive automation assembly systems (A3Ss) through digital technologies and intelligent automation to manage the assembly of a wide range of product variants and different features of human operators. Although some qualitative studies attempted to conceptualize such systems introducing their key features and identifying the main system requirements, so far, real industry-oriented framework, A3S design approaches and prototypes, and numerical analysis to a benchmark such innovative systems toward traditional ones are still missing and expected. This paper expands the lacking research on A3Ss proposing a reference framework guiding toward their effective design and validation. The proposed framework is, then, applied to a full-scale prototype, named Self-Adaptive Smart Assembly System (SASAS), describing its features together with the productivity and ergonomic improvements arising from its implementation. Compared to traditional assembly, the proposed assembly workstation allows us to reduce the assembly cycle time (up to 38.6% in the proposed experimental analysis) and the human worker movements during the activities with productivity increase (up to 62.8%) and the enhance of the ergonomic work conditions (REBA index reduction of about 15% in the proposed experimental analysis). Results show the benefits in terms of productivity, flexibility, and ergonomic performances derived from adopting the advanced assembly prototype making such a system of interest and applicable to industry. Starting from this evidence, extensions in theory and practice are encouraged. The former deals with the inclusion of the economic and environmental dimensions to the proposed framework, embracing a holistic multi-objective methodology, the latter includes the framework application to industry and the SASAS prototype industrialization, customization and spread to multiple industrial sectors.

Author Contributions: Conceptualization, M.B., M.F., F.G.G. and M.G.; methodology, M.B., M.F., F.G.G. and F.P.; writing—original draft preparation, M.F. and F.G.G.; writing—review and editing, M.B. and M.G.; supervision, M.B., M.F. and M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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