Handbook of Manufacturing Systems and Design

An Industry 4.0 Perspective

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6 Collaborative Robots

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6.1 INTRODUCTION

Market globalization and mass customization are pushing industries to move past the conventional mass production paradigm and focus on adopting innovative technologies with humans (as workers and customers) as the core of the production system (Kleindienst et al., 2016). Industry 4.0 is framed to help companies meet the new global demands and reform the industrial environment (Laudante, 2017). One of the main features of Industry 4.0 is to enable the factory of the future by including new types of intelligent information systems and automation as well as more flexible collaborative robots called "cobots." The purpose of this chapter is to elaborate on the role that "cobots" have in the well-known era of Industry 4.0.

6.1.1 What Are Collaborative Robots or "Cobots"?

According to ISO/TC 299, a collaborative robot or cobot is defined as a robot designed to interact directly with humans in a defined collaborative space (Faccio et al., 2022). The idea of collaborative robots was introduced by Colgate, Edward, Peshkin, and Wannasuphoprasit (Colgate et al., 1996), who focused on the simplest possible version with only a single joint, also known as a steerable wheel. Since then, several versions of cobots with different technologies embedded in them have been introduced in the market (Baumgartner et al., 2020).

According to the International Federation of Robotics (IFR), the market for cobots is still growing, and the end-users and engineers are still exploring the best configuration in terms of sensors, grippers, and intuitive programming interfaces for

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FIGURE 6.1 Cobots from different manufacturers (adapted from https://www.universal-robots.com/, https://crx.fanuc.eu/ch-fr/, https://www.kuka.com/en-de/products/robot-systems/industrial-robots/lbr-iiwa, https://new.abb.com/products/robotics/robots/collaborative-robots/yumi/irb-14000-yumi, https://industrial.omron.fr/fr/products/collaborative-robots, https://www.doosanrobotics.com/en/Index).

their efficient design and implementation in the manufacturing sector (IFR, 2020). Cobots from different manufacturers are shown in Figure 6.1.

The primary purpose of cobots is to be used in a shared workspace along with a human worker without fences to perform tasks involving varying levels of interaction. Different types of interactions are possible in a shared working environment, namely, coexistence, synchronization, cooperation, and collaboration (Baumgartner et al., 2020; Chiabert & Aliev, 2020; Fast-Berglund & Romero, 2019; Malik &

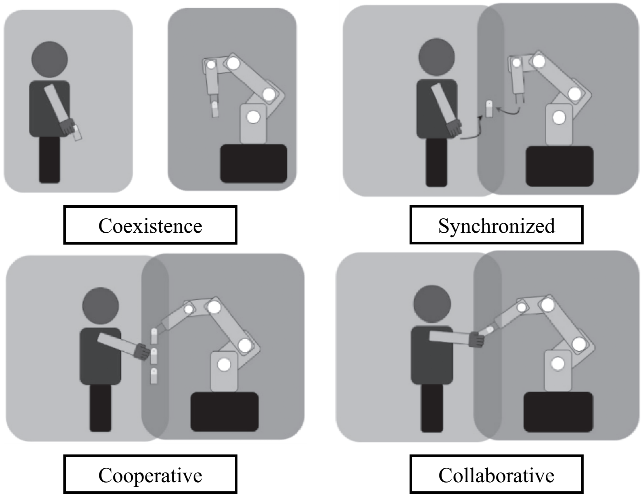

FIGURE 6.2 Schematic representation of different robot interactions (adapted from Dzedzickis et al., 2021).

Bilberg, 2019; Wang et al., 2019; Villani et al., 2018). Coexistence interaction exists when the worker and robot are close to each other without sharing the workplace. For synchronized interaction, the workspace is shared between the worker and robot but not at the same time. The task is completed in sequence, with the worker and the robot doing their steps one after the another. During cooperative interaction, the worker and the robot are in direct contact with each other; however, they work on different tasks. The collaboration interaction involves the worker and the robot having direct contact and working on the same tasks together. A schematic representation of different robot interactions is presented in Figure 6.2.

6.1.2 Increase in Demand for Cobots

The increase in the adoption of Industry 4.0 technologies in manufacturing and the rise in various customized products has significantly increased the demand for robots in general. Conventional industrial robots are unable to meet the current market demand efficiently due to their shortcomings as they are less intelligent and flexible, costly, and time-consuming. Cobots, on the other hand, can eliminate these disadvantages by working along with humans (Gervasi et al., 2020). A detailed comparison between conventional and collaborative robots is given in Table 6.1.

The primary market for cobots is small and medium-sized enterprises (SMEs) which account for about 90% of the world's enterprises and play a significant role in global economic growth and job creation (Muller et al., 2016). Since cobots are low-cost, safe, and have plug-and-play features, they can easily be installed in SMEs to produce low-volume, high-variant products with a faster return on investment (ROI). Almost all companies have reported increased productivity due to the implementation of cobots in their manufacturing setup.

TABLE 6.1
Difference Between Conventional and Collaborative Robots (Adapted from Villani et al., 2018; Bi et al., 2021; De Simone et al., 2022)

Characteristic Feature	Conventional Robots	Collaborative Robots
Proximity to humans	Prohibited	Allowed when the procedure of safety is followed
Safety barrier	Physical separation	Safety assurance mechanisms
Robot movement	Motion with separation of human workers	Simultaneous motions of worker and robot
Footprint of robot	Large for protection	Small for collaboration
Robot control	Pre-programmed	Can be modified in-line
Robot programming	Lead-through and off-line	On-line, off-line and multimodal interaction
Programming skill	Sophisticated	Intuitive
Complexity	Fixed programs for fixed tasks	Flexible programs to handle changes and uncertainties
Tasks	Repeatable, mostly fixed	Frequent changes
Structural feature	Heavy and rigid	Light-duty and easy to move
Payload	Medium to high	Low to medium
Workspace	Isolated	Shared
Use of workspace	High	Limited
Position	Fixed	Flexible
Productivity	High	Limited
Volume of products	Used for high volume	Used for lower volume and high variants
Adaptability	Hard automation by program	Soft automation by interactions

According to a study by market data forecast, the international cobot business is expected to grow to \$12.48 billion by 2026 from its value of \$0.65 billion in 2019, at a compound annual growth rate (CAGR) of 44.8% (Globe Newswire, 2020).

With the advancement in Industry 4.0 technologies, several factors are driving the need for using cobots in manufacturing, namely: market globalization, shortening product life cycles, high product customization, labor and social cost development, demographic changes, agility and changeability, digital transformation, and so on.

6.2 IMPORTANCE OF COBOTS IN MAKING MANUFACTURING SMART

The progress of Industry 4.0 has led to several innovative technologies, which, when combined, make manufacturing bright. In addition to cobots, a few such technologies are the Internet of Things (IoT) and artificial intelligence (AI). Using cobots supported by these technologies and humans has resulted in the development of augmented intelligence (a combination of cobots' AI and authentic human intelligence). This allows the manufacturing sector to be more efficient and accurate while enhancing creativity and introducing new diversity in the workplace. Implementing cobots has several benefits, such as:

- Improvement in productivity: Cobots are better in accuracy, perseverance, and reproducibility when compared to human workers (Villani et al., 2018). This makes them suitable for implementation in repetitive tasks where production volume also needs to be achieved.
- Increase in flexibility: Due to an increase in mass customization, manufacturing companies look for solutions without losing the classical advantages of a conventional production line (Y. Wang et al., 2017). Human-cobot teams have proven to be more efficient when compared to teams consisting of humans. The collaborative feature of cobots helps perform repetitive and physically demanding tasks while the human worker can focus on complex tasks requiring high cognitive skills.
- Increasing job attractiveness: Cobots are majorly used for performing repetitive and dull manual work. This allows the workers to engage themselves in new potential value-creating activities. This also helps them expand their skill set and take on new roles and responsibilities. Additionally, reducing repetitive and physically demanding tasks has helped improve the workers' working conditions and well-being.

Other key drivers for implementing cobots in the manufacturing sector (Bauer et al., 2016) are shown in Figure 6.3.

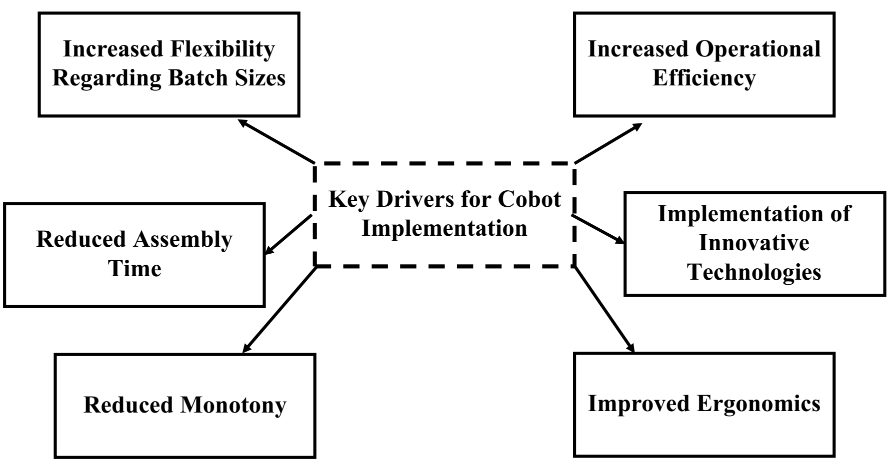

FIGURE 6.3 Key drivers for implementing cobots in manufacturing industries (adapted from Bauer et al., 2016).

6.3 NEED FOR COLLABORATION BETWEEN ROBOTS AND INDUSTRIAL WORKERS

There needs to be more clarity among the public about the introduction of robotic technology in the automation field. This is due to the common presumption that all the jobs and occupations of the workers will be replaced by robots, resulting in fear of job loss. However, a more accurate perception can be understood from the statistical study from the US Bureau of Labor and McKinsey Global Institute (McKinsey & Company, 2017), which states that 18% of the time consumed to accomplish a job is wasted in predicted activities that can be automated with a success rate of 78%. Also, 12% of the time consumed is spent on predictable activities, which have a low success rate (around 25%) of automation. In manufacturing, there are scenarios where the success rate of automating predictable activities is just 60%. Hence, manufacturing still has predictable and unpredictable tasks that cannot be automated fully and need human workers to accomplish them. Therefore, there is a definite need for an environment where workers and robots can collaborate to perform tasks efficiently.

6.3.1 Cobots as an Essential Tool to Achieve Industry 4.0

The shortage of skilled workers in recent years, especially in developed countries like Japan, the USA, and many countries in the EU, has affected manufacturing companies as they struggle to recruit qualified engineers and skilled production workers (McCarthy & Richter, 2020). According to a Deloitte report (2018), in 2018, it took companies 23 days longer to fill vacancies compared to 2015. Hence, employers compete for appropriate personnel in the labor market and make considerable efforts to increase their chances of recruiting suitable personnel. Large companies' reputation and publicity, and financial capabilities often allow them to offer higher salaries, making finding appropriate staff even more challenging for SMEs. Also, the younger generation has an opposing view on the manufacturing industry due to reports of offshoring manufacturing activities and jobs being dull, dangerous, dumb, and dirty (Skevi et al., 2014). All these factors have led to cobots being considered an attractive solution for relieving employees from physically and mentally stressful tasks, thereby increasing job attractiveness. Additionally, industries also believe that using cobots in their production line helps raise their reputation as innovative employers, which will attract a young and technology-driven workforce (Kopp et al., 2020).

6.3.2 Importance of Workers in Manufacturing

The ability of human workers to adapt dynamically to unpredictable tasks makes them irreplaceable in any manufacturing line involving a wide variety of products. One such example is building the interiors of an aircraft, where the tasks to be performed are more human-dependent than robots as they can adapt themselves much more efficiently. Human workers can use their natural senses intuitively to find instant solutions to complicated problems without wasting much time. For example, for the assembly of electronic devices, finding a standard way to connect

TABLE 6.2
Typical Strengths of Humans and Cobots (Adapted from Kopp et al., 2021)

Human Strengths	Cobot Strengths
Flexibility	Endurance
Perception	Power
Sensorimotor abilities	Reproducibility
Handling of different components (soft, moving, flexible etc)	Precision
Instant planning and action capability	Speed (except in collaboration mode)

some very tiny parts is extremely difficult to achieve with a robot compared to a human worker. Human workers' most significant advantage is their accumulated experience and logical judgment, which still needs to be achieved using robots.

A team of cobots and human workers provides a perfect synergy by combining the strengths of human beings and robots, which results in a superior working system (Selevsek & Köhler, 2018). Table 6.2 shows the typical strengths of humans and cobots (Kopp et al., 2021).

6.4 CHALLENGES IN IMPLEMENTING COBOTS IN MANUFACTURING

The introduction of cobots in any manufacturing environment faces challenges and difficulties. This chapter section aims to highlight these challenges and their necessary mitigation strategies.

One of the foremost vital challenges is the occupational safety issues when cobots are installed to work alongside the workers (Kopp et al., 2021). The reason for this is that the entire working system must be considered in the risk analysis in addition to the cobot itself (Kopp et al., 2020; Grahn et al., 2018). Such risk analysis is usually time-consuming and complex as it gives rise to many dynamic parameters that are difficult to envisage before its actual working in the environment. It is also important to note that the risks must be identified and eliminated (Mateus et al., 2019). In the work of Mateus et al., the authors have highlighted specific hazards grouped according to their hazard paths between the origin and the affected person (Mateus et al., 2019). These hazards might occur from (i) robots during human-robot collaboration, (ii) the process involved during the collaboration, or (iii) malfunctions in the control system of the robot during collaboration. The primary safety standards for applications of industrial robot systems are ISO standards 10218–1 (ISO, 2011a) and 10218–2 (ISO, 2011b).

Additionally, the guidelines for designing and implementing a collaborative workspace and its risk assessment are provided by ISO TS 15066 (ISO, 2016). However, more specified safety standards are needed as ISO TS 15066 is just an addition to the existing robot directive (Holm & Schnell, 2022). There is also the need to redefine safety in collaborative environments by considering the skill level of the workers and the tasks to be performed by the robots (Fast-Berglund et al., 2016).

The safety standards must also be redesigned due to the presence of conventional industrial robots and collaborative robots in the same manufacturing plant (Wang et al., 2019). This needs advanced risk assessments involving hazard identification, risk evaluation, and reductions during the early stages of the manufacturing layout planning (Gervasi et al., 2020; Poot et al., 2018).

The second challenge, a classical barrier in adopting cobots, is the fear among employees of being replaced by them (Richert et al., 2018). Industry specialists have already reported that full automation, a scenario where humans are removed from manufacturing, is not viable (Kolbeinsson et al., 2018) and that establishments should focus on creating shoulder-to-shoulder cooperation between the workers and different types of intelligent machines (Wurhofer et al., 2014). Hence, companies must present cobots as supportive colleagues to their workers rather than replacement machines. A study by Salvini et al. (2010) reports that this fear is one of the predominant factors hindering the acceptance of cobots among workers. One way to address this fear is by explaining the difference between conventional automation and cobots. They are not used to eliminate humans but to support them in collaborative working conditions.

The next challenge the companies face is getting workers' trust in cobots. This is very important during the installation and the operation phase to get the desired results as it indicates the relevance of worker-related aspects. Without trust, the worker may underutilize the robot, possibly reducing performance or even not using it (Gervasi et al., 2020). The workers' trust in cobots depends on social and emotional factors (Sadrfaridpour & Wang, 2017). A successful human-robot interaction conceptualizes trust as a prerequisite (Broadbent, 2017). Establishing trust begins before the actual physical implementation of the cobot. There is a difference between the initial trust prior to actual interaction and dynamic trust during interaction (Kopp et al., 2021).

According to one of the most comprehensive trust models in the domain of automation (French et al., 2018), trust is divided into dispositional, situation, and learned trust. Of these, dispositional and major situational factors can hardly be influenced. At the same time, the learned trust, which is a result of the worker's mental model of the robot, is dependent on the characteristics of the robot and is continuously modified by experiences (Ewart, 2019). Lewis and Walker reported that the actual reliability of the robot mainly determines the level of trust, which increases gradually when the worker becomes familiar with the robot through contact with it (Lewis et al., 2018). The initial trust can also be established by following efficient internal top-down communication strategies. These strategies work toward developing an appropriate mental model to allow positive experiences during an interaction. One thing to note here is that to reduce the impact of a single negative experience, many positive experiences are needed (Flook et al., 2019; Desai et al., 2013). The physical configuration of the robot (type of design) can also influence the trust built by the worker in the robot. For example, a giant robot may intimidate a worker into collaborating, while a more miniature robot may make the worker feel more comfortable (Gervasi et al., 2020). Three elements should be considered while assessing the worker's trust, namely (Charalambous et al., 2016), the robot, human, and external elements. The robot element considers performance (speed, movement, reliability, etc.) and physical aspects (dimensions, appearance, etc.). The human element includes safety, trust, previous experience with robots, and the human cognitive model. Finally, the external element is related to the complexity of the activity (De Simone et al., 2022).

Another challenge the decision makers face is choosing the appropriate robot configuration depending on the production process, tasks to be done by the worker and the selected cobot, and the positioning of the functional materials. This is because not all processes require a cobot to be used. It also means that the optimal workstation configuration should be planned (Turja & Oksanen, 2019). Due to the need for more well-defined standards, procedures, and steps, implementing cobot solutions require more work (Holm & Schnell, 2022). This requires the SMEs to have a precise robotics and automation strategy to implement a successful cobot application. The lack of expertise in this domain can result in choosing too complex automation tasks or involving too high interaction levels (Fast-Berglund & Romero, 2019).

One of the lesser challenges is the financial factors in introducing cobots. Generally, the costs are categorized as acquisition, maintenance, and operational costs. It has been reported that the impact of operational costs is more from a long-term perspective (Kopp et al., 2021). This is because the acknowledgment of value added to the industrial worker and the cobot needs to be clarified in teams consisting of workers and cobots, and the total costs exceed the one-time acquisition costs of the robot itself (Ranz et al., 2018).

6.5 COBOTS IN MANUFACTURING – CASE STUDIES

6.5.1 Case Study – Cobots in a High-variant Low-volume Manufacturing Line

One of the best applications of cobots has been in the high-variant low-volume manufacturing sector. One example is from Scott Fetzer Electrical Group (SFEG), an electronics manufacturer from Tennessee, USA. They have used robots to take over the workers‘ repetitive and potentially hazardous tasks (UR, 2016a). By doing so, they could use their experienced workers to perform more rewarding and value-added tasks, which in turn increased their employee satisfaction as they felt more valuable.

They used a mobile and flexible cobot fleet (cobots on rolling carts) which were easy to transport between different workstations. Since the cobots had safety features already embedded in them, the company did not need any additional safety fences or other surrounding safety sensors. This helped the high-variant low-volume company to use the robots where necessary and make the optimum use of the existing machinery, as shown in Figure 6.4.

6.5.2 Case Study – Cobots in Automotive Assembly Lines

One of the earliest implementations of cobot was done in the automotive assembly lines of an Indian automotive company (Bajaj Auto Ltd.) in 2010. Assembly lines in any manufacturing plant are highly labor intensive, require high precision, and face space challenges.

FIGURE 6.4 Use of cobot in low-volume, high-variant manufacturing line (adapted from UR, 2016a).

The specific features the company looked for in a cobot included flexibility in programming and installation, affordability, compactness, lightweight, and safe to work alongside humans (UR, 2016c). These features were chosen to improve the productivity, flexibility, and reliability of their assembly line along with the ergonomics for the company workers (finding the right kind of working position to eliminate work-related musculoskeletal disorders). They installed cobots from Universal Robots (UR) in their assembly line with a typical pitch dimension of one meter for assembling motorcycle engines, as shown in Figure 6.5.

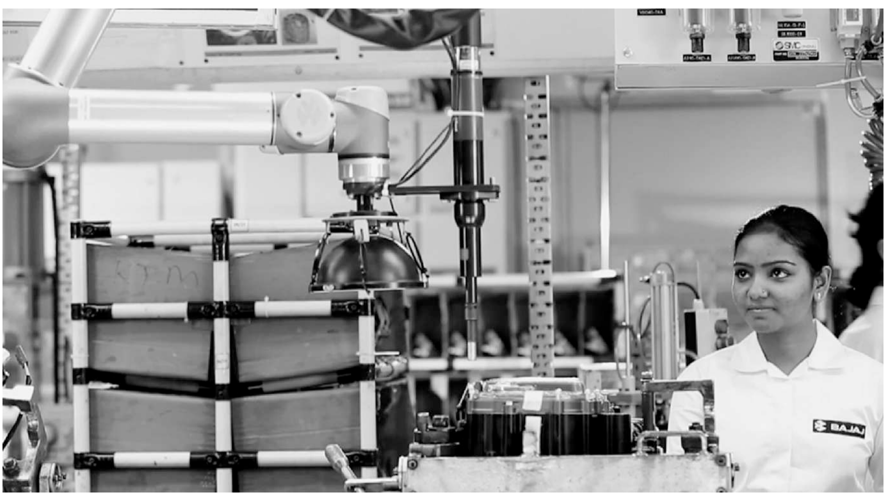

FIGURE 6.5 Cobot setup used by Bajaj Auto for automotive assembly tasks (adapted from UR, 2016c).

Following the successful installation and integration of cobots in 2010, they currently have more than 100 cobots for various applications such as machine tending, material handling, and engine assembly. Their inclusion has increased the personnel productivity at the company from 507 to 804 vehicles per person per year. Cobots have also helped remove barriers for women in an assembly line and increased their participation to 50% of the total workforce. This contrasts with the widespread belief that the introduction of cobots leads to job losses.

6.5.3 Case Study – Integration of Cobots in Automotive Manufacturing

Continental automotive factories in Spain integrated cobots into their manufacturing line to increase market competitiveness and productivity (UR, 2016b). Having already been exposed to the advantages of automation and IoT due to the introduction of Industry 4.0, they were keen on using cobots for monotonous and repetitive tasks such as gluing, dispensing, and validating the printed circuit boards produced by the company.

Due to the salient safety features already available in cobots, the company was able to install them very quickly and was able to achieve a rapid return on investments (ROI) (less than 24 months). They also achieved a 50% reduction in their changeover time, which was reduced from 40 minutes before the introduction of cobots to 20 minutes afterwards. A cobot installed by the company is shown in Figure 6.6.

The easy programming methods available for cobots from UR helped the workers develop programs for the final products much faster than before, accelerating their implementation.

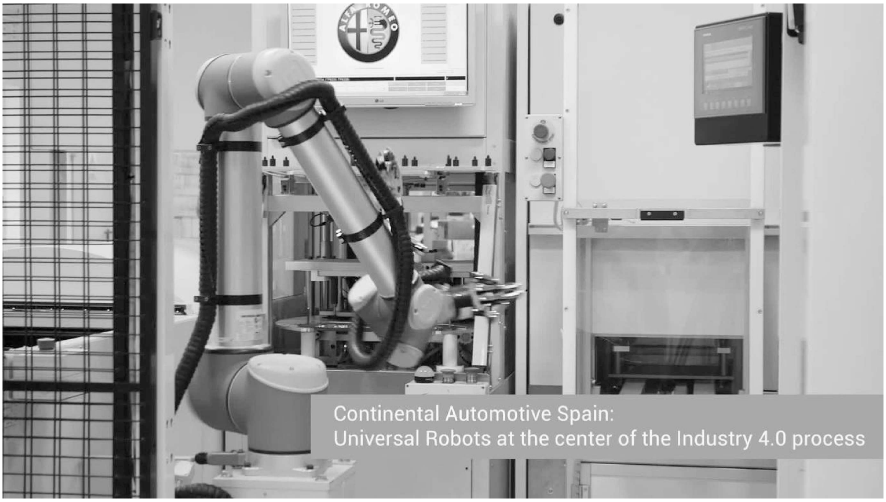

FIGURE 6.6 Cobot used by Continental Automotive for automating tasks (adapted from UR, 2016b).

6.5.4 Case Study – Assembling Fiat 500 Electric Car

Stellantis N.V., a Dutch company, installed 11 cobots from UR at its assembly plant in Turin, Italy, to automate complex assembly line operations and quality controls for the new Fiat 500 electric car (Crowe, 2022). They installed the cobots for a wide range of operations such as the application of waterproof liner to the vehicle doors, positioning of the soft-top using tracking and visual inspection, checking the soft-top frame dimensions, riveting of the tailgate, mounting the hood, tightening of the door hinges, and mudguard mounting. They used a mix of UR5 and UR10 cobots depending on the tasks. The setup used by the company is shown in Figure 6.7.

The company took steps in gradually introducing the cobots to help the operators fully understand their characteristics. They were first introduced in the company canteen, where their operators could interact with the cobot (which was tasked with the distribution of glasses of water during lunch break). This allowed the workers to observe the safety and collaborative features of the cobot by themselves and overcome inhibitions in accepting them in their working environment.

The company benefited from implementing cobots in all the applications they selected. Due to cobots' high repeatability and ability to follow complex paths easily within a confined space, they obtained high operating precision, increased productivity, and quality, along with better ergonomics and working conditions for their operators.

6.5.5 Case Studies from FANUC CRX Cobots

FANUC, being the largest maker of industrial robots in the world, has developed several models of cobots that have been implemented for different applications

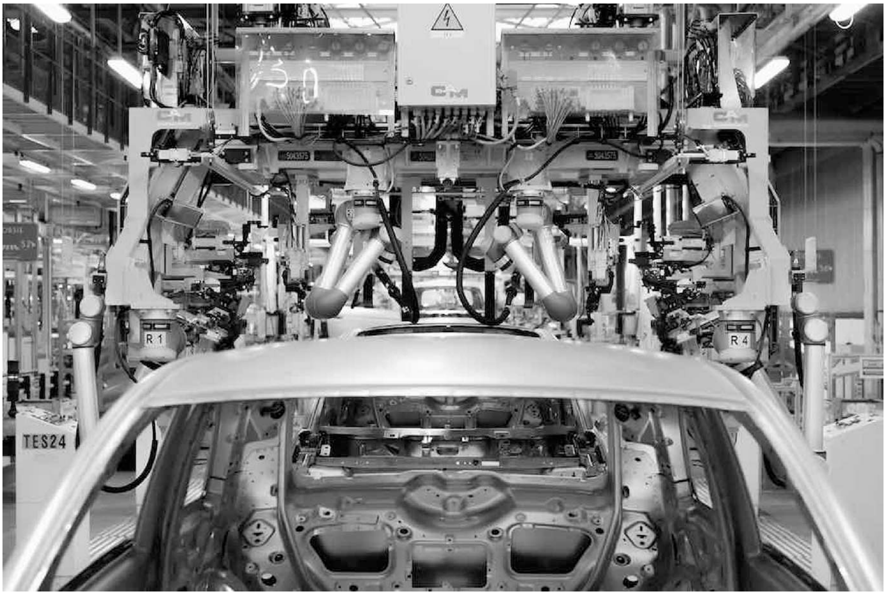

FIGURE 6.7 Setup of the cobots used for assembling Fiat car (adapted from Crowe, 2022).

worldwide. Some of the recently implemented cobot solutions are presented here as case studies:

6.5.5.1 Lights-out Production Using FANUC CRX Cobots

Collaborative robots from FANUC, also known as FANUC CRX Cobot, have been used by Athena 3D Manufacturing company to achieve lights-out0 production (https://www.fanucamerica.com/case-studies/athena-3d-manufacturing). The printers that completed their jobs in the middle of the night were forced to sit idle until the next morning when the operator changed out the print bed to start the next job, which was highly time-consuming and impacted machine utilization and production deadlines. Using the collaborative robots from the FANUC CRX series, the company was able to quickly scale production from one to multiple printers, all running at the same time, all night long, because of which they were able to double their production with a 40% increase in machine utilization. This enabled the employees to focus more on product quality as well.

6.5.5.2 Case Study – Automated Welding Operation Using FANUC CRX Cobots

Last Arrow Manufacturing, an Ohio-based contract manufacturer, used FANUC CRX welding cobot to develop a flexible automated solution to perform simple and repetitive welding projects (https://www.fanucamerica.com/case-studies/all/last-arrow-manufacturing). This has helped them in increasing their productivity, freeing up their skilled welders to carry tasks requiring more expertise. They also achieved high employee satisfaction with improved flexibility and higher profits.

6.5.5.3 Case Study – Integrating Mobile Cobots with FANUC CRX Cobots

One application of integrating a collaborative mobile robot with a collaborative industrial robot can be seen at an Austrian company, GER4TECH (https://www.ger4tech.at/en-g4t4/). They have integrated G4T4 (a mobile cobot) with FANUC CRX-10iA/L. These mobile cobots can move autonomously between different workstations, transport materials, and switch from one job to another without any trouble. The company has used them to handle applications for machine tools, transportation of raw materials and finished parts, pick and place applications, warehouse picking, etc.

Further applications using FANUC CRX cobots can be found in Success Stories – YouTube.

6.6 CONCEPTUAL FRAMEWORK

Different frameworks and models are available for introducing cobots in a manufacturing line. Each framework follows different principles. Eekels and Roozenburg (1991) used an engineering design cycle, Ranz et al. (2018) proposed a framework using the quantitative and qualitative conceptual and technical aspects of human-robot interactions, and a generic two-dimensional design and implementation framework was proposed by Djuric et al. (2016). Further explanation of the models and framework can be found in Kopp et al. (2021).

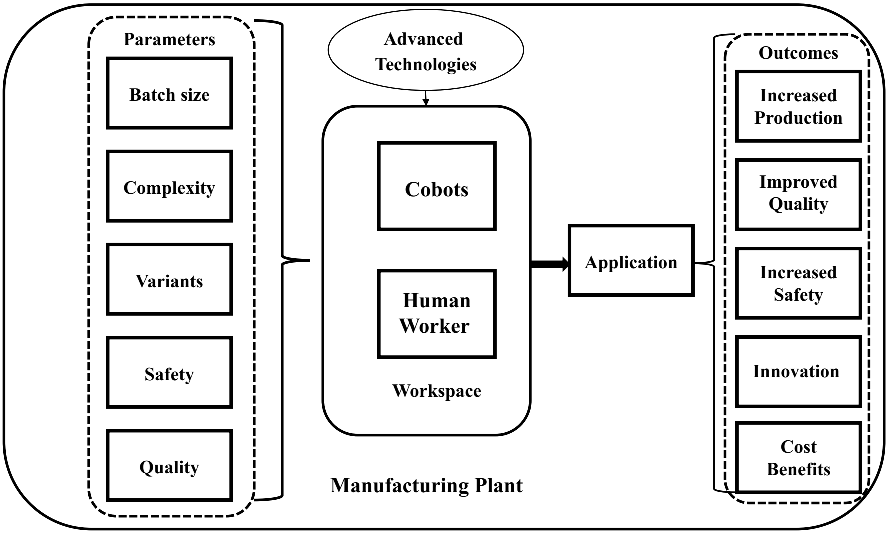

FIGURE 6.8 A simplified conceptual framework for implementing cobots in a manufacturing line.

A simplified conceptual framework is proposed for the readers as a starting point to check for the use of cobots in a manufacturing line. This framework is adapted from the work of (Kopp et al., 2021). The framework is shown in Figure 6.8. It takes into account the parameters that should be considered when the need for implementing a cobot for a manufacturing line is being planned.

6.7 CONCLUSION

As more SMEs and companies start implementing Industry 4.0 along with cobots for their production line, considerable modifications are expected in the production processes. Changes are foreseen on different levels, namely, work content, work organization, production management, and other organizational factors (Badri et al., 2018; Waschneck et al., 2016). These changes will result in the manufacturing systems being self-learning with the ability to make decisions by themselves. Such systems will incorporate the creativity and adaptability of human workers and help these workers in assuming more leadership and supervisory roles on the shop floor (Khalid et al., 2018).

Future research should explore more in detail which work can be usefully automated, what should be the optimum level and complexity of collaboration in such automated tasks and how it will affect the cognitive workloads of the human workers, the required skills and training needed to achieve it to reach the level needed for a booming Industry 4.0 implementation.

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