A framework for hazard identification of a collaborative Plug&Produce system

Bassam Massouh, Sudha Ramasamy, Bo Svensson and Fredrik Danielsson [1]

[1] Department of engineering science, University West, Trollhättan, Sweden

Abstract. Plug&Produce systems accept reconfiguration and have the attribute of physical and logical flexibility. To implement the Plug&Produce system in a manufacturing plant, there is a need to assure that the system is safe. The process of risk assessment provides information that is used to implement the proper safety measures to ensure human and machine safety. An important step in the risk assessment process is hazard identification. Hazard identification of Plug&Produce system is unique as the hazard identification method provided in the safety standards do not consider system flexibility. In this paper, a framework for hazard identification of collaborative Plug&Produce system is presented. A study case that includes a collaborative Plug&Produce system is presented and the framework is applied to identify the system's hazards. Also, the generalisation of the framework application is discussed.

Keywords: Plug&Produce, Collaborative robots, Risk assessment, hazard identification.

1 Introduction

Reconfigurable manufacturing systems (RMS) are designed for rapid change in the structure to adjust the production output within the same part family in response to the requirements[1]. The concept of Plug&Produce system is built upon the concept of RMS. A Plug&Produce system has the capability of instant and automatic physical reconfiguration, and the capability to adapt intelligent control assurance logic. Plug&Produce possess the attributes of logical flexibility and physical flexibility. Logical flexibility refers to system ability for facilitated replanning, reprograming, and rescheduling. Also, physical flexibility refers to system ability for facilitated change in the layout, machines, and material handling devices. A human worker can be considered as the most flexibles component of the manufacturing system and the involvement of human worker in the manufacturing system add flexibility to the system. A collaborative operation is an industrial operation performed by human and robots working side by side and collaborating to achieve the task. The collaborative work between the human and the robots raises safety challenges.

To realize the industrial application of the Plug&Produce system, it is required to assure that the system is complying with safety standards. To ensure the safety of the system according to standards, risk assessment is needed to be performed and to perform risk assessment, it is required to identify the hazards. Hazard identification process must consider the flexibility of the system and the possibility of system reconfiguration. The safety standards can be used to assess the safety of a flexible system. However, the existing standards do not consider flexibility.

In this study, a framework to identify the hazards of a collaborative Plug&Produce system is presented. The study discusses risk assessment according to standards and describes the process of hazard identification within the risk assessment. Then the study discusses hazard identification for collaborative operations and hazard identification for Plug&Produce systems. A framework for hazard identification of collaborative Plug&Produce system is derived. A collaborative Plug&Produce system with several reconfiguration scenarios is presented as a study case and the framework is applied to identify the hazard of the system in the presented study case. Also, the generalisation of the framework application is discussed.

2 Background

2.1 Plug&Produce systems

Modern manufacturing systems have some critical requirement such as short lead-time, high variety of the products and fluctuating production volumes with low production cost. To meet the requirements several strategies are developed based on the reconfigurable manufacturing concept [2]. The concept of Plug&Produce is inspired by the concept of Plug and Play in the computer world. It is described as an agile manufacturing system that accepts reconfiguration in a short time and has distributed control system over the manufacturing devices[3]. One framework for the Plug&Produce considers the system as a system of several self-aware and modular production process modules with a distributed control strategy based on a multi-agent system [4]. New devices plugged into the Plug&Produce system are identified automatically and instantly allowing for making changes in the system in a short time [5].

A Plug&Produce system contains resources, and resources have skills. To achieve the production goals, the system generates process plans. A process plan is a sequence of skills that are utilised to achieve the goal. The skills are utilised without specifying the resource which allows the system to achieve the goal if resources are changed. [4]

2.2 Collaborative robot system

The objective of collaborative robots is to combine the repetitive skills of the robots with the cognitive skills and abilities of the human. A collaborative robot system is a system designed in a way that the operator and the robot share the workspace. The robot in the collaborative robot system is just a component and the associated cell layout is designed to eliminate the hazard. The operational characteristics of the collaborative robot system are different from the traditional robot systems. In collaborative operations, the operator can be in proximity with the robot while the actuators of the system are powered. [6]

Human-Robot Collaboration opens new possibilities for industries and adds additional flexibility to industrial production. New robotic applications are enabled by a human-robot collaboration including robot assistance in welding tasks and assembly processes, human assistance and ergonomic support and machine tending and material handling.[7] [8]

Plug&Produce systems allow quick and easy adaptation of collaborative operations in the manufacturing processes. The modular integration of collaborative operations within Plug&Produce allows achieving the collaborative operation goals regardless of the participating resources.[9][10]

2.3 safety standards

The standard ISO 12100 gives an overview of the basic principles and methodology for hazard identification, risk assessment and risk reduction. The standard also defines basic terms that are related to risk assessment. Harm is defined as physical injury or damage to health. Hazard is defined as the potential source of harm. Risk is defined as the combination of the probability of occurrence of the hazard that generates the harm and the severity of the harm.[11]

The standard ISO 10218 specifies the requirements and provide a guideline for safe design and use of industrial robots, and describes the hazards associated with robots and provides requirements to eliminate the hazards. The standards provide definitions for terms. Collaborative operation is defined as the state in which specifically designed robots work in collaboration with a human operator within the same defined workspace. The collaborative workspace is a workspace within the safeguarded zone in which the human and the robot perform the collaborative operation. [12]

The standard ISO 14121 gives a guideline to conduct risk assessment in accordance with ISO 12100 and provides tools and methods to achieve the actions included in the risk assessment. It also provides examples of measures to reduce risks. [13]

The standard ISO 15066 specifies the safety requirements for collaborative robot system and the work environment. It provides a guideline for hazard identification, risk assessment and risk reduction associated with collaborative robot systems. [6]

ISO 10218 and ISO 15066 identify four collaborative methods. Safety-rated monitored stop, Hand guiding, Speed and separation monitoring and Power and force limiting. [6][12]

Safety-rated monitored stop includes that the operator performs manual tasks inside a collaborative area, which is an operative space shared between the human and the robot. Inside such a collaborative area, both the human and the robot can work, but not at the same time since the latter is not allowed to move if the operator occupies this shared space.

In the hand guiding method, the operator can teach the robot positions by moving the robot without the need of an intermediate interface, e.g., robot teach pendant.

The speed and separation monitoring method allows the human presence within the robot's space through safety-rated monitoring sensors.

The power and force limiting collaborative method prescribe the limitation of motor power and force so that a human worker can work side-by-side with the robot.

The current collaborative methods given by the standards are similar to traditional automation and don't support the implementation of an intelligent collaborative system. A new type of collaborative method named deliberation in planning and acting is proposed, in which the robot and the operator deliberate and execute an agreed-upon plan. [14]

There is a possibility to change between operational modes, the collaborative, and non-collaborative mode. When the collaborative mode is activated, it is indicated clearly to the operator with light indicators. The sensory system is adjusted to allow the human presence in the collaborative workspace without causing a safety stop. Robot speed at the collaborative mode is adjusted to ensure human safety according to the performed risk assessment. [15]

3 risk assessment and hazard identification

The process of risk assessment provides information that is used to implement the proper safety measures to ensure human and machine safety. The general strategy for risk assessment is provided in ISO 12100 and a practical guideline for achieving the risk assessment activities is provided in ISO 14121 The procedure of a system risk assessment includes the following actions, in the order given:

1. Determine the limits of the machinery, which includes the limitation of the machine in space and defining the intended use and reasonably foreseeable misuse.
2. Identify the hazards and the associated hazardous situations.
3. Estimate the risk for each identified hazard.
4. Evaluate the risk and decide the need for risk reduction.

The objective of determining the limitation of the machine is to have a clear description of the machine properties, the use and possible misuse and the environment in which the machine will be operated and maintained. The objective is achieved by an examination of the functions of the machine and the tasks associated with the use of the machine.

The objective of hazard identification is to list all hazards and hazards associated situation which allows describing the hazard scenario. Hazard identification methods must consider the human interaction with machines during the entire life cycle of the machine, the possible operating conditions and modes of the machine, and the unexpected behaviour of the operator or reasonably foreseeable misuse of the machine.

Risk estimation is the process to understand the nature of the risk and determine its magnitude which results from combining the consequences and their likelihood. It starts by addressing the severity of the harm. There are levels of severity of harm. It combines the level of severity with the probability of occurrence of the harm. The combination leads to determine the level of the risk.

Risk evaluation is the process of comparing the results of risk estimation with applied protective measures to determine if the hazardous situation requires further risk reduction. Also, to determine if the risk reduction has been achieved without introducing new hazards or raise the level of other risks.

3.1 Hazard identification of collaborative robot system

Standard ISO 15066 defines risk assessment for a collaborative robot system, as the need to identify the hazards and estimate the risk of a collaborative robot system so the proper risk reduction methods measures are implemented. The hazard identification process of collaborative robot operation in a collaborative robot system considers the robot-related hazards such as robot characteristics, robot contact conditions and the proximity of the operator to the robot. Also, it considers the hazard related to the robot system including the end-effector and workpiece hazard and operator location with respect to hazardous fixtures. To identify the hazards of a collaborative operation, the collaborative operation is divided into several tasks, each task is allocated to the robot or the human operator and allocated to a workspace. Each task is then analysed to identify the hazards. [6]

Task-based hazard identification of collaborative operations is discussed in [16][17][18]. The safety design of the collaborative robot system focuses on individual hazards within the collaborative workspace rather than keeping the operator away from the hazardous zone [19].

3.2 Hazard identification for Plug&Produce systems

Risk assessment of Plug&Produce comprises of determining the limit of the machines, hazard identification, risk estimation and risk evaluation. The modularity feature of the Plug&Produce system makes the procedure of risk assessment specific. The Plug&Produce system is modular and consists of several process modules, and each process module can be considered as a system itself.

A system of systems consists of several autonomous systems. A Plug&Produce system can be considered a system of systems [20]. Two types of hazards are identified in the system of systems. The two types of hazards are single system hazards and emergent hazards [21][22]. Relative to the Plug&Produce concept, the single system hazards are associated with hazards of a single module while the emergent hazards are associated with the hazards that are generated when several modules are configured in the Plug&Produce system. According to [22], emerging hazards can be subdivided into reconfiguration hazards, integration hazards and interoperability hazards.

1. Integration hazards: can be subcategorized into interface hazards, proximity hazards, resources hazards.
   - Interface hazard: a hazard in which the module transfers a hazard source to another dependent or cooperative module.
   - Proximity hazard: a hazard in one module caused by close physical proximity to another module.
   - Resource hazard: a hazard resulted from insufficient shared resources or resources conflict.
2. Reconfiguration hazards: results from a change in the system configuration from one configuration to another.

3. Interoperability hazard: it occurs when data of one module is miss interpreted by another module.

4 hazard identification of collaborative Plug&Produce system

Hazard identification of collaborative robot systems is discussed in section III.A, and hazard identification of Plug&Produce system is discussed in section III.B. based on the findings 3.1 and in 3.2, the hazard identification of a collaborative Plug&Produce system is discussed.

The risk assessment of the collaborative Plug&Produce system includes the steps of identifying the machine limitation, hazard identification, risk estimation and risk evaluation. In this study, identifying the use of process modules is considered as identifying machine limitation.

The step of hazard identification of collaborative Plug&Produce is unique due to the flexibility of the system both in hardware and control structure. The safety standards can be used to assess the safety of a flexible system. However, the existing standards do not consider flexibility. Hazard identification process must consider the flexibility of the system and the possibility of system reconfiguration. Plug&Produce system reconfiguration means that process modules are added or removed from the system, or the position of process modules and the layout of the physical system is changed. Also, in a Plug&Produce system, the objective could be changed. Hence, the use of the same process module is changed.

4.1 Hazard identification framework

To address the unique hazard identification process of the collaborative Plug&Produce system, a framework for hazard identification is proposed. Also, a study case of collaborative Plug&Produce system is presented. The framework is applied to identify the hazard of the collaborative Plug&Produce system described in the study case. The framework includes the following steps:

1. Determine the use of each process module.
2. Identify the hazard of each module and the associated hazards situations for every use of the module.
3. Identify the emerging hazards for every foreseen reconfiguration.

4.2 Study case

To demonstrate the proposed hazard identification framework, a Plug&Produce cell is presented in this study case. **Fig. 1** shows the presented Plug&Produce cell. The cell consists of an industrial robot in the centre of the cell and several positions for Plug&Produce process modules. Two process modules are included in the cell with different configurations. Process module 1, shown in **Fig. 2**, includes an inherently safe designed collaborative robot and a surface space. Process module 2, shown in **Fig. 3**, includes an industrial robot and a surface space. When process module 1 is configured in the system, the shared accessible collaborative workspace is indicated to the operator, and the worker understands that it is safe to be in the shared collaborative workspace.

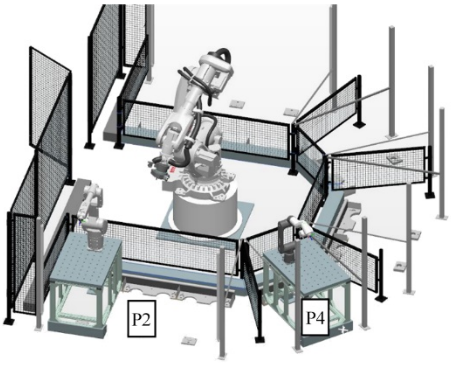

Fig. 1. Plug&Produce cell

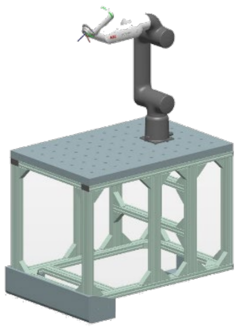

Fig. 2. Module 1

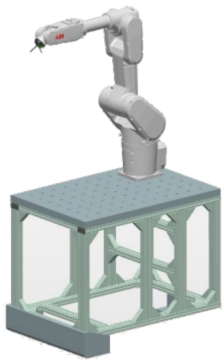

Fig. 3. Module 2

In the presented Plug&Produce system, three foreseen reconfigurations can be identified. The reconfigurations are:

1. Reconfiguration1: change of the use of the collaborative process module

Module 1 is used to perform two collaborative operations. the use of the collaborative module changes based on the produced part. The first collaborative operation is assembly, and the second collaborative operation is grinding. The first operation contains the following steps:

- The industrial robot in the centre of the cell carries a workpiece and place it on the table of the collaborative module.
- The operator prepares a part.
- The collaborative robot picks the part and places it in its intended position in the workpiece.

Also, the cell produces another product using the second collaborative operation. The part that the operator prepares, needs grinding performed by the collaborative robot. The worker then picks the finished part and place it in position in the workpiece. The second operation contains the following steps:

- The industrial robot in the centre of the cell carries a workpiece and places it on the table of the collaborative module.
- The operator prepares a part.
- The collaborative robot performs grinding on the part.
- The worker picks the part and places it in position.

2. Reconfiguration2: change the location of the collaborative module.

The second configuration is the change position of module 1 i.e., the change of the cell layout so the collaborative module is in a different position. The collaborative module location is changed from position 4 indicated in the figure by P4 to position 2 indicated on the figure by P2.

3. Reconfiguration3: change the collaborative module with a different module.

The third reconfiguration is to change module 1 with module 2. The assembly operation objective does not change. However, the assembly operation is not collaborative. The operator does not participate in the assembly operation. The operator job of preparing the parts is done outside of the robot workspace and then a batch of the prepared parts is brought to the processing module to achieve the assembly operation.

4.3 Hazard identification of the study case

The first two steps in the framework are to identify the use of the process modules and to identify the associated hazards. **Table 1** presents the identified hazards for module 1, **Table 2** presents identified hazards for module 2. The modules have defined uses, and the hazards associated with assembly operation are different depending on the module that is used to perform the assembly. Module 1 includes a robot that is safe inherently designed, so the power and force of the robot's motor are limited to element the hazard of collision between the robot and the worker body.

The third step is to identify the emerging hazards from every foreseen reconfiguration of the system. **Table 3** lists the identified emerging hazards of every foreseen reconfiguration.

Table 1. Module 1 identified hazards

Module 1					
Module use	**Life cycle**	**Task**	**Hazard zone**	**Hazard**	**Hazardous situation**
Assembly	Operation	Pick & Place	Shared work-space with the worker	Head or body injury	Worker in the shared workspace and the contact with the part carried by the robot happens due to loss of part control
Griding	Operation	Grinding the surface	Shared work-space with the worker	Head or body injury	The grinding wheel bursts, and parts of the grinding wheel hits the worker
				Eye injuries	Debris from the grinding operation flies and reach the operator's eyes
				Body part burn	Grinding results in heat and contact with hot material causes burn

Table 2. Module 2 identified hazards

Module 2					
Module use	**Life cycle**	**Task**	**Hazard zone**	**Hazard**	**Hazardous situation**
Assembly	Operation	Pick & Place	Shared work-space with the worker	Head or body injury	Worker in the shared workspace and the contact with the part carried by the robot happens due to loss of part control
		Pick & Place	Shared work-space with the worker	Head or body injury	Worker in the shared workspace and the contact with robot happens due to robot movement

Table 3. Identified emerging hazards

Reconfiguration	**Emerging hazard type**	**Hazard**	**Hazardous situation**
Reconfiguration1	Resource hazard	Body or head injury.	Use of a process module with high power load becomes included in the system which causes electricity overload. The system shut down unexpectedly and in an unsafe manner.
Reconfiguration2	Proximity hazard	Body or head injury.	Module 1 and module 2 become in proximity and the contact between the robot in module 2 and the operator happens due to the robot movement.
Reconfiguration3	Interoperability hazard	Body or head injury.	The human faultily interprets the indicators that the workspace is not collaborative, and contact happens due to the robot movement.

5 Conclusion

Plug&Produce systems have physical and logical flexibility. Including collaborative operations in the Plug&Produce system increases flexibility. Guidelines provided in safety standards can be used for hazard identification of collaborative Plug&Produce system. However, safety standards do not consider flexibility. The hazard identification of the highly flexible collaborative Plug&Produce is unique. A framework to identify the hazards of a collaborative Plug&Produce system is proposed in this paper. The framework is used to identify the hazards of a collaborative Plug&Produce cell presented in a study case. The generalisation of the framework is then discussed. The generalisation of the framework is faced with challenges. These challenges are related to the extended effort needed to identify all emerging hazards due to many possible reconfigurations of the system. Also, due to the complexity of identifying the hazards of such a highly flexible system, there is a need to verify that all hazards are identified.

A possible improvement to the framework is to automatically identify the hazards. Information that can be used to identify the hazards such as the functional and the physical attribute of the process module along with the use of the module are stored in a database. A software that is programmed to perform the proposed framework for hazard identification, uses the stored hazard-related information and automatically identifies all the hazards. The software is programmed with a verification method to ensure all hazards are identified. The development of the verification method for hazard identification and the development of the software for automatic hazard identification is an interesting topic for future research.

References

[1] H. A. El Maraghy, "Flexible and reconfigurable manufacturing systems paradigms," *Flex. Serv. Manuf. J.*, vol. 17, no. 4 SPECIAL ISSUE, pp. 261–276, 2006, doi: 10.1007/s10696-006-9028-7.

[2] Z. M. Bi, S. Y. T. Lang, W. Shen, and L. Wang, "Reconfigurable manufacturing systems: The state of the art," *Int. J. Prod. Res.*, vol. 46, no. 4, pp. 967–992, 2008, doi: 10.1080/00207540600905646.

[3] T. Arai, Y. Aiyama, Y. Maeda, M. Sugi, and J. Ota, "Agile assembly system by `Plug and Produce'," *CIRP Ann. - Manuf. Technol.*, vol. 49, no. 1, pp. 1–4, 2000, doi: 10.1016/S0007-8506(07)62883-2.

[4] M. Bennulf, F. Danielsson, B. Svensson, and B. Lennartson, "Goal-oriented process plans in a multi-agent system for Plug & Produce," *IEEE Trans. Ind. Informatics*, pp. 1–1, 2020, doi: 10.1109/tii.2020.2994032.

[5] M. Bennulf, F. Danielsson, and B. Svensson, "Identification of resources and parts in a Plug and Produce system using OPC UA," *Procedia Manuf.*, vol. 38, no. 2019, pp. 858–865, 2019, doi: 10.1016/j.promfg.2020.01.167.

[6] SIS (Swedish Standards Institute), *Robots and robotic devices – Collaborative robots, (ISO/TS 15066:2016, IDT)*. 2016.

[7] C. Thomas, B. Matthias, and B. Kuhlenkötter, "Human - Robot Collaboration – New Applications in Industrial Robotics," *Int. Conf. Compet. Manuf.*, no. January, pp. 293–299, 2016.

[8] E. Matheson, R. Minto, E. G. G. Zampieri, M. Faccio, and G. Rosati, "Human-robot collaboration in manufacturing applications: A review," *Robotics*, vol. 8, no. 4, pp. 1–25, 2019, doi: 10.3390/robotics8040100.

[9] C. Schou and O. Madsen, "A plug and produce framework for industrial collaborative robots," *Int. J. Adv. Robot. Syst.*, vol. 14, no. 4, pp. 1–10, 2017, doi: 10.1177/1729881417717472.

[10] M. Wojtynek, J. J. Steil, and S. Wrede, "Plug, Plan and Produce as Enabler for Easy Workcell Setup and Collaborative Robot Programming in Smart Factories," *KI - Kunstl. Intelligenz*, vol. 33, no. 2, pp. 151–161, 2019, doi: 10.1007/s13218-019-00595-0.

[11] SIS (Swedish Standards Institute), *Safety of machinery - general principles for design - Risk assessment and risk reduction(ISO 12100:2010)*. 2010.

[12] SIS (Swedish Standards Institute), *Robots and robotic devices – Safety requirements for industrial robots – Part 1: Robots (ISO 10218-1:2011)*. 2011.

[13] SIS (Swedish Standards Institute), *Safety of machinery – Risk assessment – Part 2: Practical guidance and examples of methods (ISO 14121-2:2012, IDT)*. 2015.

[14] A. Hanna, K. Bengtsson, P. L. Götvall, and M. Ekström, "Towards safe human robot collaboration - Risk assessment of intelligent automation," *IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA*, vol. 2020-Septe, pp. 424–431, 2020, doi: 10.1109/ETFA46521.2020.9212127.

[15] V. Gopinath, F. Ore, S. Grahn, and K. Johansen, "Safety-Focussed Design of Collaborative Assembly Station with Large Industrial Robots," *Procedia Manuf.*, vol. 25, pp. 503–510, 2018, doi: 10.1016/j.promfg.2018.06.124.

[16] V. Gopinath, K. Johansen, and J. Ölvander, "Risk Assessment for Collaborative Operation: A Case Study on Hand-Guided Industrial Robots," *Risk Assess.*, 2018, doi: 10.5772/intechopen.70607.

[17] V. Gopinath, K. Johansen, Å. Gustafsson, and S. Axelsson, "Collaborative Assembly on a Continuously Moving Line - An Automotive Case Study," *Procedia Manuf.*, vol. 17, pp. 985–992, 2018, doi: 10.1016/j.promfg.2018.10.105.

[18] V. Gopinath and K. Johansen, "Risk Assessment Process for Collaborative Assembly - A Job Safety Analysis Approach," *Procedia CIRP*, vol. 44, pp. 199–203, 2016, doi: 10.1016/j.procir.2016.02.334.

[19] T. Hull and M. A. Minarcin, "Considerations in Collaborative Robot System Designs and Safeguarding," *SAE Int. J. Mater. Manuf.*, vol. 9, no. 3, pp. 545–551, 2016, doi: 10.4271/2016-01-0340.

[20] J. M. Aitken, R. Alexander, and T. Kelly, "A risk modelling approach for a communicating system of systems," *2011 IEEE Int. Syst. Conf. SysCon 2011 -*

Proc., pp. 442–447, 2011, doi: 10.1109/SYSCON.2011.5929099.

[21] C. H. Koo, S. Schröck, M. Vorderer, J. Richter, and A. Verl, “A model-based and software-assisted safety assessment concept for reconfigurable pnp-systems,” *Procedia CIRP*, vol. 93, pp. 359–364, 2020, doi: 10.1016/j.procir.2020.03.076.

[22] P. J. Redmond, J. B. Michael, and P. V. Shebalin, “Interface hazard analysis for system of systems,” *2008 IEEE Int. Conf. Syst. Syst. Eng. SoSE 2008*, 2008, doi: 10.1109/SYSOSE.2008.4724202.