Doctoral School of Regional Sciences and Business Administration

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# Measuring the complexity inherent in robot-human interaction

Summary of doctoral dissertation

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# 1. Introduction

“The only things you can measure are: the time and the distance.”

## 1.1. Industry 4.0

If you type to internet search engine “Industry 4.0”, then you will get more million hits. Among the first results of this quest are German companies such as: Siemens, Kuka AG, Deutsche Telekom, Robert Bosch, then government bodies such as the German Trade & Invest, Platform Industrie 4.0, even the European Parliament, and also some consulting companies such as PWC, Mckinsey, BCG. There are similar key words as well: for example the “Internet of Things”, “smart production”, “Industrial Internet” in the United States, or “Catapult” in the United Kingdom. All these indicate that a technological jump has started. Several organisations use the same key words and try to get attention, indicating that they want to take part in the fourth industrial revolution. It is hard to determine their degree of involvement, more and more institutes, advising companies make their own assessment criteria to judge this.

## 1.2. Human-robot collaboration

Human-robot collaboration, a new application, is increasing and facilitating collaboration without fences, cages or any kind of separation. Complexity level of implementation is relative low and as a smart working has an “easy adaptation” in the complexity of Industry 4.0 technologies (Franka, et al., 2019).

Industrial robots usually have physical separation such as cages, fences, barriers, and lasers, outlining their restricted space. Collaborative robots, also called “cobots” (Peshkin & Colgate, 1999), can function together with their operators in an uncaged environment. Such design enables safe collaboration between humans and robots with a reduced risk of injuries and collisions. The wires and motors in cobots are internal. External surfaces and edges are rounded to reduce potential injuries. Cobots have built-in sensors to detect external forces and to stop or return to park position in case of contact or collision not pre-programmed. An advantage of deployment of a robot is that it is easy to teach the robot—the operator can show it the desired movement and it can then replicate that movement accurately. The advantage of the robot’s replicating accuracy, and agility and ability to produce repetitive work combined with human capabilities opens a new era in manufacturing. The European manufacturers seems to be leading the way in human-robot collaboration (Bogue, 2016). The collaborative robot market is estimated to reach a total value of USD 12.303 million by 2025 (marketsandmarkets, 2019)

## 1.3. Objective of this thesis

In the previous paragraphs, the Industry 4.0 and the human robot collaboration are briefly introduced. Going deeper into the field, the aim of this dissertation is to give an overall picture about the human robot collaboration through a detailed literature review, identify potential research possibilities and gap in literature, familiarize with object detection technology, determine management view on human robot collaboration, describe methodology of the objective judgement of the human robot collaboration, apply in a real collaboration and as a sample evaluate it.

# 2. Literature review and gap

The purpose of this chapter is to review mainstream academic publications to evaluate the current status of human-robot collaboration and identify potential areas of further research. A systematic literature review is offered that searches, appraises, synthetizes, and analyses relevant works. This review reports the prevailing status of human-robot collaboration, human factors, complexity/ programming, safety, collision avoidance, instructing the robot system and other aspects of human-robot collaboration. It identifies new directions and potential research in practice of human-robot collaboration, such as measuring the degree of collaboration, integrating human-robot collaboration into teamwork theories, effective functional relocation of the robot and product design for human robot collaboration (DHRC).

In recent years, increasing number of publications on human-robot interaction have become available. Therefore, a review of the literature is relevant, informing the evolving directions. A review by Hentout et al. covers publications between 2008 and 2017 and proposes a categorisation of the collaborative applications such as hardware, software design, safety, cognitive interactions, robot programming, task allocations, virtual and augmented reality, physical interaction and fault tolerance (Hentout, et al., 2019). An earlier review by Tsarouchi et al., presents task planning/coordination/allocation and reviews programming, scheduling, metrics for human robot interaction and the social aspects. The role of digital human modelling systems, the process of learning by demonstration as well as the instructive systems are also reviewed, focusing on programming through visual guidance and imitation, voice commands and haptic interaction (Tsarouchi, et al., 2016).

### 2.1. Conclusion of the literature review and future work

The actual and predicted market growth of the human-robot collaboration in industrial environment makes this review necessary. It is imperative that the academic world follows up with appropriate and adequate research to influence and contribute to this rapidly emerging trend. This systematic literature review answers two questions:

What is the actual status of human-robot collaboration research in industrial environment?

What are the potential future directions and research possibilities of the human-machine interaction in a manufacturing context (gap in the literature)?

Based on the scope of this study, the specified key words, time period, and the application of inclusion and exclusion criteria, 87 articles were selected from high quality journals. After reading these articles, the following categories were created where mainly technical aspects published: the *collaboration*, as the process of working together to complete a task; *complexity* in the context of integrating all components; *programming* as a link between the different peripheries; *robot system safety*, as first priority in fenceless collaboration; *collision*, the consequences of an event; *instructing the robot system*, as transferring the desired motion. Non-technical side as part of the integration the *human aspect* was published.

Gap in the literature and directions for possible future research have been proposed, such as *measuring the level of collaboration*, improving *communication* between human and robot, and exploring the human issues including qualification and *personal traits.* Also it is suggested that going forward, research focus on integration of the *robot as a team member*, use of *big data analysis* for optimization of human-robot collaboration. The *industrial views and needs*, *upgrading* opportunities of existing equipment, and *flexibility* in deployment are important aspect of applying robots. Human-robot collaboration is a complex topic. This paper has identified some possible research directions that are important for further development and *design for human-robot collaboration* (DHRC). Several design rules could be defined for effective human robot collaboration. Each topic is worth deeper investigation, in this thesis measuring the human robot collaboration examined profound.

## 3. Methodology and Propositions

The result of the literature review indicates, besides several points, that measuring the human robot collaboration is still an unexplored field (gap in literature).

### 3.1. Assessment, measurement of the human robot collaboration

Participants of the human robot collaboration judge the outcome of the joint effort through reliance, success, failure, and the human's perception of the robot to reality. If the judgement is precisely calibrated, then the interaction will presumably be optimal. There are several studies to map the human side, mainly focusing on the trust development in the collaboration. Trust is an important element to consider because the presence or absence of it affects the outcome of the collaboration. Hancock et al. identified several factors of trust development in the human robot interaction (Hancock, et al., 2011). Published study (Nelles, et al., 2018) maps the collaboration mainly through questionnaires, different tasks, methodologies, sample sizes and results. See a few examples in *1. Table* . The questionnaire-based assessment may have disadvantages such as the number of participants, representation of age, male/female ratio, nationality, cultural differences, and previous experiences. The formulated question, the interpretation, the used scale, the reliability of answers, and the behaviour in real situation are main concerns when interaction is investigated.

| Study | Participants | Method | Number of participants |
|---|---|---|---|
| *Metrics and benchmarks in human-robot interaction: Recent advances in cognitive robotics* (Aly, et al., 2017) | conference, and online participants | questionnaire | 50 |
| *WHAT! You Want Me to Trust a ROBOT? The Development of a Human Robot Interaction (HRI) Trust Scale* (Yagoda, 2011) | subject matter experts within academia, government, and industry | questionnaire<br>3-point Likert scale | 11 |
| | crowdsourcing web service, Amazon online participants | questionnaire<br>7-point Likert scale | 100 |
| *Facilitating Human–Robot Collaborative Tasks by Teaching-Learning-Collaboration from Human Demonstrations* (Wang, et al., 2019) | no experience of using the TLC model to work with robots. | questionnaire<br>5 point Likert scale | 9 |
| *The Development of a Scale to Evaluate Trust in Industrial Human-robot Collaboration* (Charalambous, et al., 2016) | 21 participants (14 males) from Cranfield University, 20 had no experience with robots | interview | 21 |

*1. Table Mapping collaboration at different studies (source: own elaboration)*

Earlier studies mentioned gesture recognition based on images (marker, single camera, stereo camera, depth sensor) and non-image technology (glove, band, sensor). The collected data are mainly used to improve the non-verbal communication with the robot. (Liu & Wang, 2018). A study also focuses on communication through human eye movement tracking compared to human head tracking (Palinko, et al., 2016). There is an objective measurement through gesture recognition and physiological parameters that provide more reliable information about the real interaction. *See* 2. Table

| Study | Participants | Method | Number of participants |
|---|---|---|---|
| *Effects on User Experience during Human-Robot Collaboration in Industrial Scenarios* (Pohlt, et al., 2018) | right-handed participants who frequently use technical devices (18), students (13) | gesture recognition | 18+13 |
| *Assessment of operator stress induced by robot collaboration in assembly* (Arai, et al., 2010) | not detailed | Operator stress measured through physiological parameters | 5 |
| *Physiological and subjective evaluation of a human robot object hand-over task* (Dehais, et al., 2011) | Healthy volunteers (12) were recruited by local advertise-ment. young (mean age: 26.5), male(10) and female (2),right-handed, postgraduate | sonars, laser, stereo camera banks, several contact sensors and a wrist force sensor | 12 |

*2. Table Measurement of the collaboration in human-robot interaction (source: own elaboration)*

However, the above mentioned studies do not investigate the *ongoing* collaboration, the focus lies on oral feedback about the experience *after* the collaboration. In the researches when ongoing collaboration with sensors investigated, it is complicated and limited due to the used non-friendly solution.

The proposed object detection has the capability to detect *ongoing* collaboration, based on *behaviour* and in the meantime more user friendly, no sensors, or wires attached to human participants.

### 3.2. Object detection

Recently, object detection has become a rapidly developing technology related to computer vision and image processing. It detects objects with high probability on digital images, videos and provides object information such as category, position, direction. It is also able to identify pre-defined patterns and is able to track the movement of the identified object. In recent years, the deep-learning based approach (Guo, et al., 2016), (Zhao, et al., 2019), (Dhillon & Verma, 2019), (Ciaparrone, et al., 2020) has gained advantage due to the easy application and high chance for correct object detection. This technology uses training data adaptively, has flexible and high generalization ability. Widely used methods are the (1) region-convolutional neural network (RCNN), (2) faster region-convolutional neural network (Faster RCNN), (3) You Only Look Once (YOLO) and (4) single shot multibox detector (SSD). See the major milestones in the history of object detection in *Figure 1*.

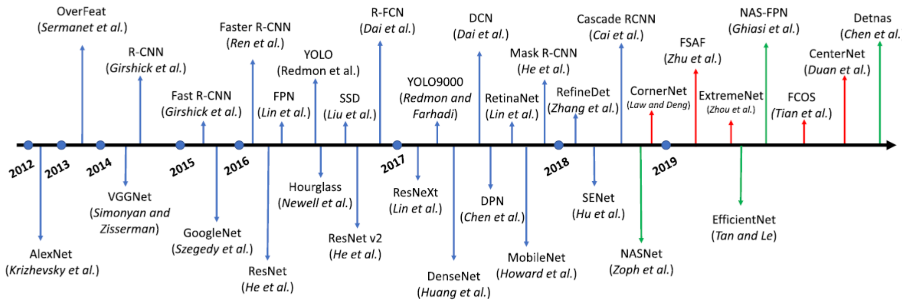



*Figure 1: Major milestones in the history of object detection (Wu, et al., 2020)*

This technology is widely applied for surveillance (Fu, et al., 2019), vehicle detection (Fan, et al., 2016), autonomous driving (Lin, et al., 2017), Security control already applies object recognition on images to identify pre-defined articles and items that are not allowed at airports. Such a deep-learning-based algorithm can identify object with a 97.1% accuracy using *YOLO* (You Only Look Once) technique (Dhiraj & Jain, 2019). This approach divides the input images into 13×13 grid cells, each being responsible for predicting 5 bounding boxes for each anchor, performing all this in a single network, which makes it faster and real-time.

Video detection-YOLO

The deep learning technology can detect objects on images with high accuracy and it is also fast enough to compute a high number of figures. You Only Look Once (YOLO) is a network for object detection in video images that bypasses the disadvantages of the slow detection speed and high time consumption (Redmon, et al., 2016). YOLO converts the object detection to extract the features from images directly and calculates the bounding boxes and probabilities of the categories. Thereupon, it obtains the object categories and position information and adopts a single convolutional neural network to predict the multiple bounding boxes and probabilities of the categories. It means that the YOLO divides the images into S×S grids and then, for each object and grid, it calculates the probability of the centre of the objects falling within the grids. If the probability exceeds a threshold value, it is determined that there is an object in the grid. Boundary boxes are built for the grids with objects, and the confidence level of each box is computed simultaneously. The confidence level reflects the probability that the boundary box contains the object (Lu, et al., 2019). For the system model (Redmon, et al., 2016).

There are several challenges in the use of the object recognition technology, for example: (1) the influence of the background on images, (2) the changing speed of background environment, (3) light variation, (4) frames/second in a video, (5) the training strategy of the system, (6) the object detection speed, (7) the detection of small and dense objects, (8) the speed of the detectable object, (9) the size change of the object, distance near-far, (10) object only partly on the image, (11) the problem of overlapping objects, (12) the problem of the multiple object tracking, (13) high computational and memory requirements.

### 3.3. Managerial judgement

During implementation process, decision makers, managers, leaders in formal or informal positions at the company mirror the company's interests and policy. The key players can form the need for objective assessment, measurement of human robot collaboration and use the object detection as a tool.

One main question still open: which aspect of the human-robot collaboration is important to key players? There are trade-offs during the implementation, for example profitability versus human work-load reduction. The human robot collaboration initiates a change in the organisation; therefore, we can place the collaboration's different aspects into the McKinsey 7S framework (Waterman, et al., 1980). It reflects the dilemma of a productive organization: find the right balance among *strategy, systems, structure, skills, style, staff* and *superordinate goals*. The right balance decides the organisation; there are no starting point or implied hierarchy.

*Structure* in the human robot collaboration raises aspects such as complexity, dividing the tasks between human and robot, coordinating function and central support. Structural change caused by the new collaboration such as guidance methods, usage of contact sensors, vision systems, wearable devices.

*Strategy* towards the human robot collaboration indicates topics such as company plan response to changes (older workforce, technology change), implementation speed of new technology, usage and/or upgrade of existing structure, ergonomic/work load perspective.

*System* used in the production needs to function together with robot; it raises the issue of integration to existing systems, the need of new programming, handling of data collection. Further changes come along with human robot collaboration: new/changed safety procedures, security system, hardware components, mechatronic design, control and autonomy algorithms, network capacity, contacting the existing systems or create new ones.

*Style* plays an important role when robot implementation decided. Not only the physical appearance of the robot is relevant, but also the attitude and approach of the key players during the implementation phase. One aspect is the behaviour of the robot in the collaboration, such as speed, reaction, usability. Further changes are style of the communication, gestures, wearable sensors, verbal communication, user emotion recognition, cognitive aids.

*Staff* collaborates with the robot. Change of education needs, level of experience, age of actual staff, personal traits are among the aspect in the human robot collaboration. The dedicated staff for the integration are among the first pioneers. The attitude of key persons including robot manufacturer, the human in the collaboration, managers (decision makers) in the organisation, supporting personnel play major role. The robot improves the ergonomic perspective and it physically helps to the blue-collar workers.

*Skills*, competence, and ability in the human robot collaboration are represented both side: on one hand the robot capability and potential, on the other hand the know-how of the key players. Human robot collaboration initiates change through handling the speed of the robot, the safety and reliability aspects, adapting to human stability and/or instability. Competence in collision detection, change in training needs, teaching method to transfer human motions and in the meantime, keep consistency are the major challenges.

*Superordinate goals* are the guiding concept among the corporate objectives. It includes future directions with the human-robot collaboration and it keeps the focus on the innovation, new technology, profitability decisions. Possible changes are workplace re-organisation, work execution on different level, potential identification and effect on profitability, increase efficacy, conflict with the acceptance and union, handling the fear of losing jobs, human safety concern, social influence, emotional interactions, and external view.

The human judgement is a process through which an individual uses social information to make decision. The judgement depends on the individual's environment, past experiences, training and interpretation of available information. The social judgement theory (Cooksey, 1996) can help to model the managerial judgement in the human robot collaboration. The model is based on Brunswik's book (Brunswik, 1952) and considered one of the most usable decision models (Dhir, 2001). The lens model and the lens model equation provides useful framework for modelling components of judgmental achievement and for creating tools to help decision makers reach better judgments (Kaufmann, et al., 2013). This model is already used to map managerial judgements (Ladinig, et al., 2020) and it is proven suitable to facilitate common decisions in uncertain situations. The so called "lens model" has been used for several applications to visualise and support the judgment in complex problems. Lens model is applied to clinical judgement (Dhir, 1987) and to healthcare where it is used the social judgement theory to model nurses' use of clinical information in critical care education (Thompson, et al., 2005). A study highlights an empirical approach to delineate how competencies should be deployed for the purpose of recruitment decisions (Akhuly & Gupta, 2014). The lens model has been used in several decision situation over the last decades. A meta-analysis that includes 249 studies using the lens model to study the way humans make decisions (Karelaia & Hogarth, 2008).

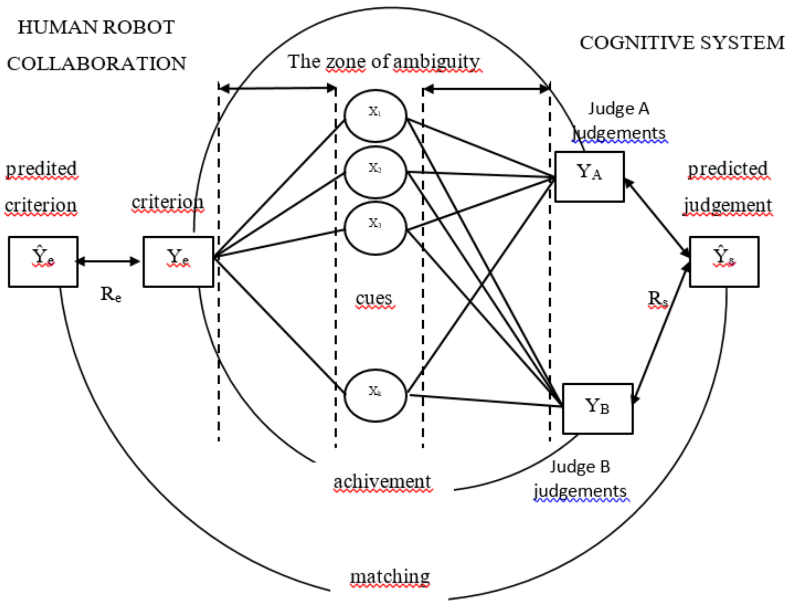



Figure 2: Author representation of lens model triple system design in the human robot collaboration based on (Cooksey, 1996)

Applying the lens model to the managerial judgement in the field of human robot collaboration highlights the problem of several factors and the trade-off possibility between the attributes. For example, increased safety through additional sensors may reduce the profitability or versatility. The situation can be described visually as shown on

*Figure* 2. The figure shows the ecology and the cognitive system of the human robot collaboration. Each system contains of one variable, $Y_e$ for the human robot collaboration system influenced by the cues $X_k$, while $Y_s$ on the right side describes how decision makers use the cue information to make judgments on the state of the system. The judgment $Y_s$ is then compared with the true state $Y_e$ to calculate the correlation between their estimates and the true state. This gives an indication about the performance of decision makers and their ability to understand how the criterion will behave under different conditions.

### 3.4. Framework and propositions

Human trust, success, failure, reality and the level of collaboration are finally visible through behaviour near the robot. When the human does not trust the robot, then he or she will avoid going near to it, and will chose a longer path. If collaboration does not work for any reason, the human may collides with the robot. If the robot does not work in the collaboration for any reason then the real human robot collaboration does not exist.

So far, human robot collaboration has been explored through questionnaires (Charalambous, et al., 2016) (Aly, et al., 2017), (Yagoda, 2011), (Wang, et al., 2019), asking the participant *after* the collaboration. In the meantime the number, age, nationality of the participants, the used scale, the questions and the application environment did not give a comparable result.

Other approaches use contact glove, band, force sensors, wires, to monitor the human reaction (Arai, et al., 2010), (Dehais, et al., 2011), (Landi, et al., 2018). Such a solution imposes constraints on the freedom of execution of the operator, which may be felt as un- necessary or disturbing, in *industrial environment not feasible*.

A few cases use camera in *experimental* set up to verify the user position, behaviour in the human robot collaboration (Pohlt, et al., 2018), (Du, et al., 2014), (Zhang, et al., 2016), (Flacco, et al., 2015).

The methodology described in the thesis is based on four different elements: the application of the object detection technology in a human robot collaboration, the assessment and pattern of the human robot interaction, the managerial judgement to trace the functional attributes of decision makers and connecting the decision's functional attributes to the pattern of object detection. The proposed method, see *Figure 3,* is the following: Observing the (1) human–robot collaboration with (2) object detection technology makes possible to (3) digitalise movement. Once the data are available, different (4) patterns are recognisable and can be linked to (5) management decisions. This methodology can investigate the real collaboration through the digitalisation of human and robot movement and based on the patterns in the movement, therefore conclusions and connections to management priorities could be drawn.

The proposed object detection has the capability to detect *ongoing* collaboration, based on behaviour and in the meantime, more *user friendly*, no sensors, or wires attached to human participants. The ongoing *real collaboration* is evaluated, even with *high number of participants*, through *more cycle*. Cameras are already in use in human robot interactions, mainly for safety. The new technology is able to detect pre-defined shapes, key points in a video. Combining the above mentioned aspects the proposed methodology investigates the following:

the object detection has not been used so far in the human robot collaboration for evaluation purposes. It is not proved that it is capable to detect the detailed movement of the human and the robot. This is the first proposition.

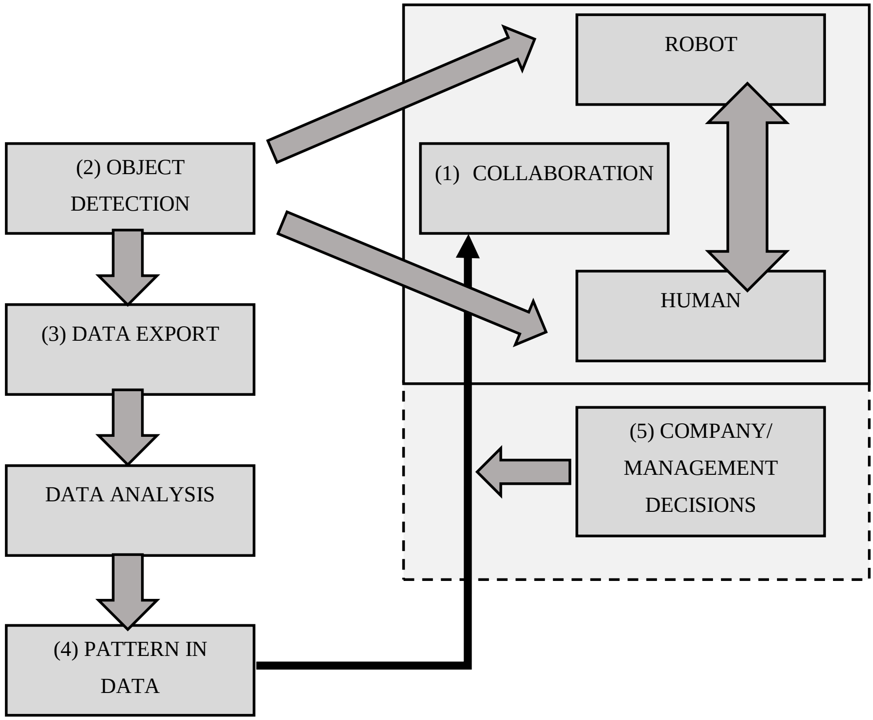



*Figure 3: Proposed framework for object evaluation of the human robot collaboration*

**Hypothesis 1:** Object detection is capable of observing the detail of the human–robot collaboration in industrial environment.

If the object detection works and is able to detect the key points of the human and the robot, this enables the evaluation of interaction between them. The detected points represent the real position of the pre-defined robot and human body parts. The relative distance to each other gives an objective picture about the interaction. This is the second proposition.

**Hypothesis 2:** Objective evaluation of the human robot interaction is possible.

The digitalisation of human and robot movement provides a huge amount of data. More cycle, more repetitive movement, more human participant result huge amount of data. This data set could be analysed, compared and different patterns may become visible. This is the third proposition.

**Hypothesis 3:** Data observed in object detection on human robot collaboration show different patterns.

Identified patterns can have different meaning and importance for different organisations. Managers of an industrial organisation have to determine, select and rank the important aspect of the human robot collaboration and translate, connect the identified patterns to the management priorities. Identifying the managerial judgements in human robot collaboration highlights the subjective factors in the judgement and helps the key player to reduce them. When the parameters of human judgement are connected to the identified patterns, this can help the decision makers to move to objective decision-making, it can reduce the unnecessary discussions and misunderstandings. This is the fourth proposition.

**Hypothesis 4:** The identified patterns can be linked to management priorities.

## 4. Results

This chapter presents the results of the application of object detection technology for human robot collaboration, based on the data collected and evaluated. Audi introduced human robot collaboration (AUDI_HUNGARIA_Zrt., 2016), where the operator works on a car while the robot makes an inspection, of course without separation, fence or cage *see Figure 4*. In the recent years, during the integration of a new car type, the collaboration was also adjusted to the change. Following the upgrade, two cameras were installed above the two robots for de-bugging reasons, to make deeper posterior technical analysis possible. During the camera installation, the rules set by the GDPR (General Data Protection Regulation, 2016) were checked, followed and fulfilled.


*Figure 4: Adam and Eve in the Vehicle Production of Audi Hungaria (AUDI_HUNGARIA_Zrt., 2016)*

The camera recorded the collaboration for a limited time period, and the company gave a permission to anonymise the video first and then to use it for evaluation and academic purposes. The data evaluation follows the predefined framework in the next chapters.

### 4.1. Object detection process

This section describes the application of the object detection methodology (YOLOv3) for human robot collaboration. The input data come from a video containing the anonymised human robot collaboration, in several cycles of the process and in clearly visible collaborative space. Further requirements of the recorded video are possible identification of cycle start or stop, light conditions, background and object contrast difference, speed of moving objects in-line with camera frame per second. The object detection process, in the investigated human robot collaboration, consists of the following steps:


*Figure 5: A frame from the video on human-robot collaboration*

| **Inputs** | **Attributes** |
|---|---|
| 1, available video, see one frame in *Figure 5* | lighting, contrast, background, focus are adjusted that humans and robots are visible, high resolution, persons are not identifiable, 2 robots (“A” and “B”) with separated video areas are visible, that means a 4 metre by 2 metre range |
| 2, identification of cycle length | 100 sec as one cycle |
| 3, start point and cycle separation | start of the cycle when mark on the conveyor belt reaches the robot |
| 4, identification and tag of human key points to follow | human ankle (left/right), knee (L/R), hip (L/R), shoulder (L/R), elbow (L/R), wrist (L/R) nose, neck, eye (L/R), ear (L/R) 18 points defined *see Figure 6.* |
| 5, identification of robot key points to follow | robot head, joint 1, joint 2, joint 3, |
| 6, false/positive filter adjustment date consistency check | definition of the max. distance between key points (for example elbow and wrist) |
| 7, identify sample taking time | video has 25 frame per second, based on human and robot operation speed 1 sample/second is evaluated |
| 8, teaching object detection | manual marking in 50 cycles, 5000 pictures are available for learning |


*Figure 6: Identified human points to follow*

| | |
|---|---|
| 9, reference system used | frame of reference defined where (0,0) is the top left corner, (1280,720) is the bottom right corner, |
| 10, object/tag position | once an object is recognised, the position is tagged and recorded in the coordinate system |

### 4.1.1. Result of object detection

The object detection methodology was successfully applied on the available videos. The algorithm catches the pre-defined tags on the robot and on the human and visualises them. As represented on *Figure 7,* the original video is on the top, anonymized, the recognised parts of the human and the robot are presented below. As the program detects human points, it connects them with green coloured lines; when the robot is recognized, then red dots and lines are used.

The process starts when the marking on the moving floor passes the basement of the robot, this is the start of a new cycle, *see Figure 8.* The robot starts the operation, parallel to the operator on the car, both of them are working on the same object, see *Figure 9.* Object recognition catches the different points and models the human robot collaboration in different situations,

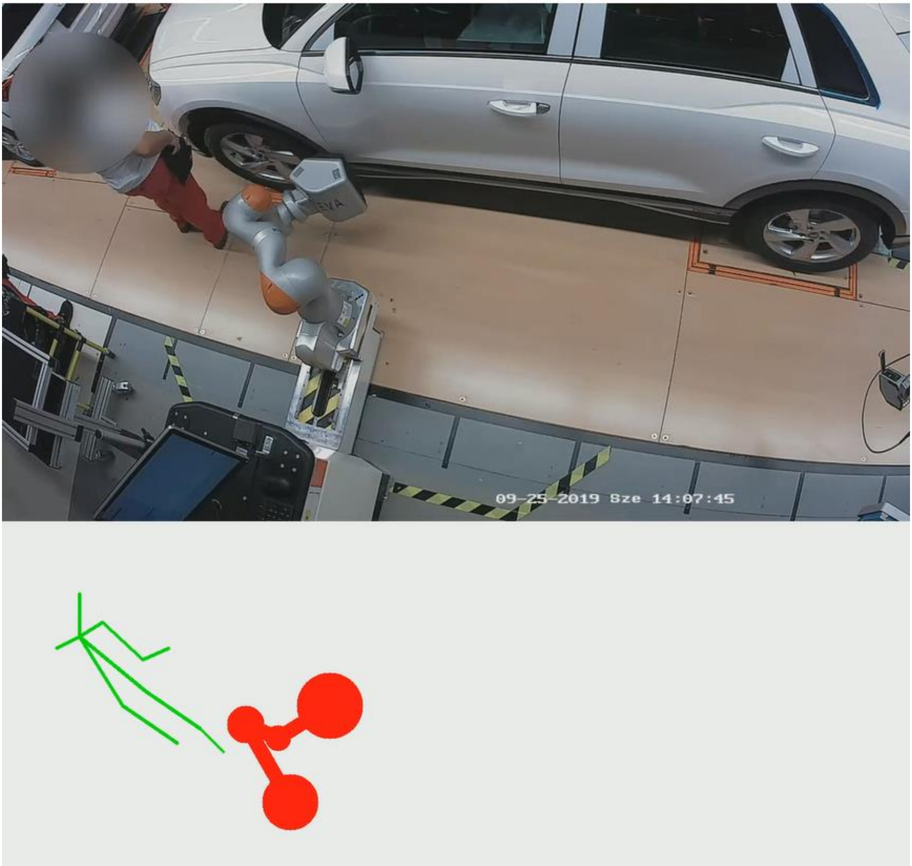



*Figure 7: Recording and visualization of the human and robot*

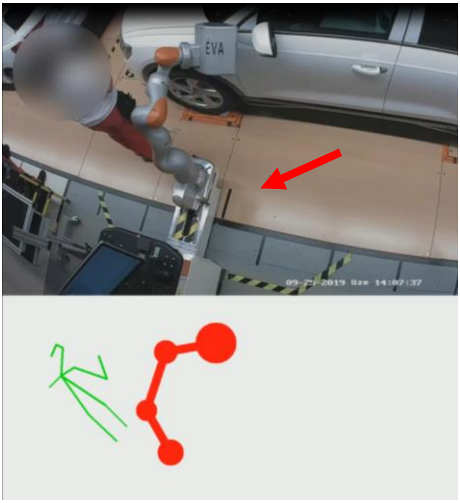


Figure 8: Process start, floor mark close to the robot

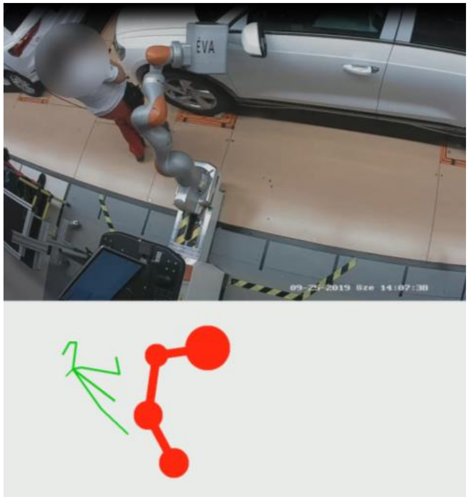


Figure 9: The robot is working on the car, the operator is starting the process

## 4.2. Result of the managerial judgement

Management members of an international car manufacturing company have been asked regarding judgment patterns and subjective preferences of team members based on their knowledge and experience. Six participants were divided to 2 functional groups: group one (Manager 1-2-3) had experience with human robot collaboration (implementation, daily usage through the organisation), the other group (Manager 4-5-6) had no experience with it, each group contained 3-3 persons. The managers selected the most important attributes from the author's literature review result and from the survey of metrics for human-robot interaction, *see Figure 10.* (Murphy & Schreckenghost, 2013)

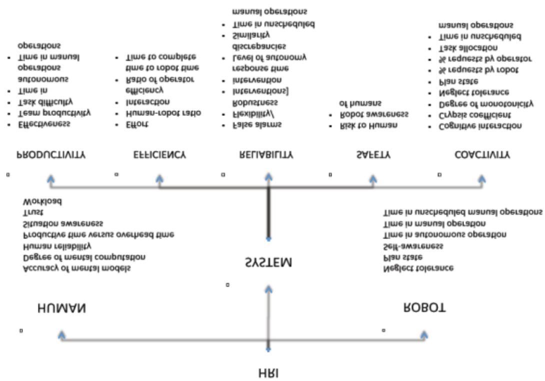



Figure 10. Taxonomy of human robot interaction metrics (Murphy & Schreckenghost, 2013)

The functional attributes of the robots deployed are chosen as follows.

- *Safety:* this attribute refers to the degree to which the deployment of the human robot collaboration is safe on the assembly line.
- *Profitability*: this attribute refers to the degree to which the deployment of the robot improves the profitability of the assembly line; that is the degree to which the deployment of the robot contributes to the overall profit.
- *Consistency*: this attribute refers to the degree to which the deployment of the robot improves the consistency of repetitive activities.
- *Work load reduction*: this attribute refers to the degree to which the deployment of the robot reduces the physical workload of human workers.
- *Versatility:* this attribute refers to the degree to which the deployment of the robot improves the versatility of application; that is the degree to which the robot can effectively and efficiently be programmed to perform a variety of tasks.
- *Stability:* this attribute refers to the degree to which the deployment of the robot ensures stability of performance, eliminating variations or fluctuations associated with humans.
- *Integration:* this attribute refers to the degree to which the deployment of the robot integrates the process, reducing the required workspace.

#### 4.2.1. Result of part 1 the priori judgment orientations

Each participant divided the 100 points among the seven functional attributes, As this is an individual judgement but the participants are part of the same organisation, the statistical analysis indicates the following: experienced managers judge the safety (average 31,7) as the most important functional attributes in the human robot collaboration, while non-experienced managers gives 13,3 points on average. Profitability is more important to the non-experienced managers (26 points), while experienced managers rated it to 14,3 points on average.

## 5. Discussion

### 5.1. Pattern in the object detention data

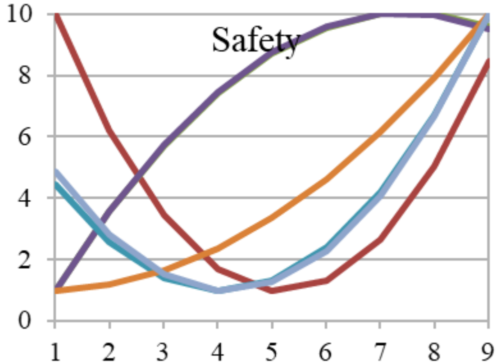
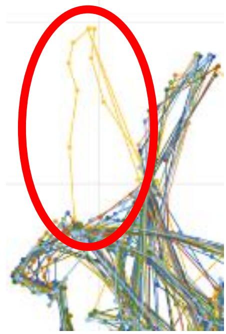
The difference between the a priori ranking and the situation based judgement confirms that managers need help, guidelines how to judge the functional attributes. Object detection and evaluation give real information about the collaboration, and the patterns in the cycle and among the repeats. Along the movement of the human in the robot collaboration, the following patterns can be recognised:

| Pattern in data | Event in the collaboration |
|---|---|
| more data are detected during the cycle | process stop within the cycle |
| no change in position | robot not working |
| postponed data from position | delay in process |
| similar data sets, reduced overlap | difference, diversity in product |
| movement to “safe” position | collision during movement |
| consequent start and stop | start and finish of the process |
| minimum distance | collaboration |
| change in minimum distance | process in the collaboration |

### 5.2. Connecting the observations to the managerial judgement

Object detection data analysis shows certain patterns and observations in the human–robot collaboration which can be linked to the management priorities. Patterns in the human movement and behaviour show a real teamwork between robot and human. Automatic observation of the collaboration can quantify the key movements which can be linked to the expectations of the management. It is also true in the other way: Management expectations regarding human–robot collaboration process can be quantified, linked to the pattern, measured, evaluated and influenced, if needed.

The management priorities are evaluated through an orientation questionnaire, as seen in chapter 5.2 above. Each attribute has an importance factor reflecting the opinion of the management about the human–robot collaboration, this judgement is connected to the recognised pattern.

| | |
|---|---|
| ***Management priority:*** ***Safety:*** this attribute refers to the degree to which the deployment of the robot collaboration is safe on the assembly line. |   *Figure 11: Management priority on safety* |
| ***Detected pattern:*** | |
| Parking position of the robot is identified and quantified during more cycles, indicating the number of possible collisions with the human or environmental obstacles. |  *Figure 12: Parking position as the result of collision* |

***Management priority:***

***Profitability***: this attribute refers to the degree to which the deployment of the robot improves the profitability of the assembly line; that is the degree to which the deployment of the robot contributes to the overall profit.

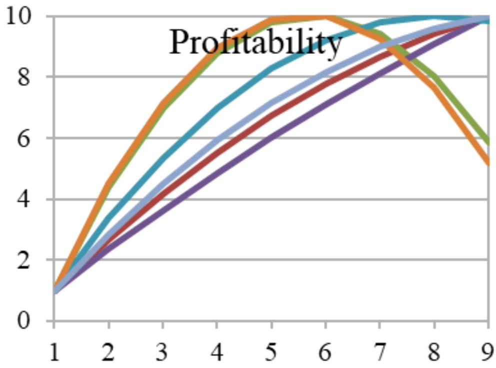



*Figure 13: Management priority on profitability*

***Detected pattern:***

No change in position indicates that the robot is not working, utilization figures are affected

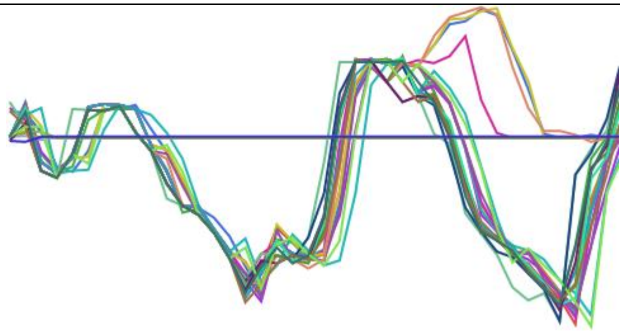


*Figure 14: No movement of the robot-utilization is affected*

Consequent start and stop are signs of a stable, effective process without interruption. Identification of the start position or end position: when the process is starting with a new component in the defined position, pushing the start button takes out finished parts.

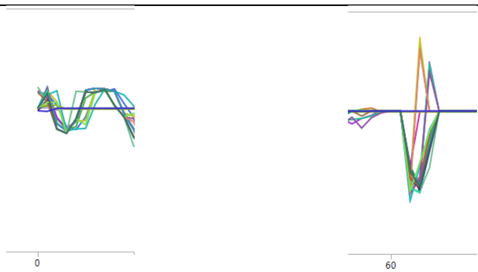
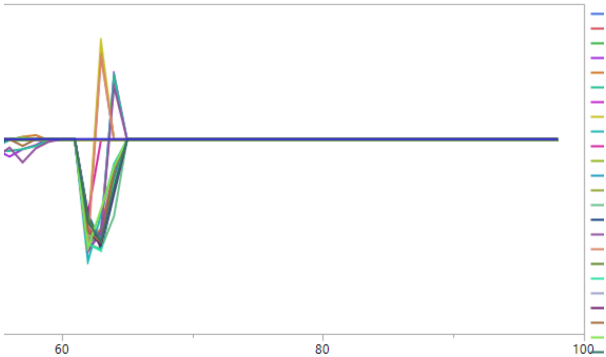
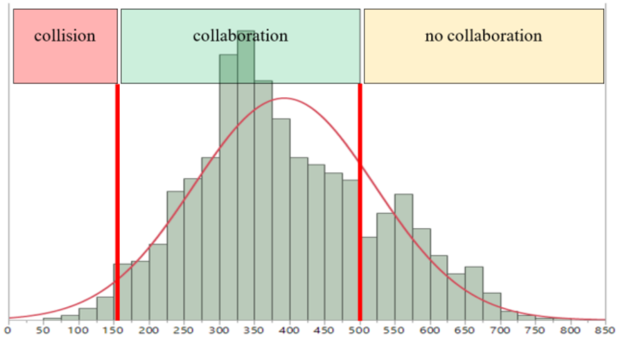
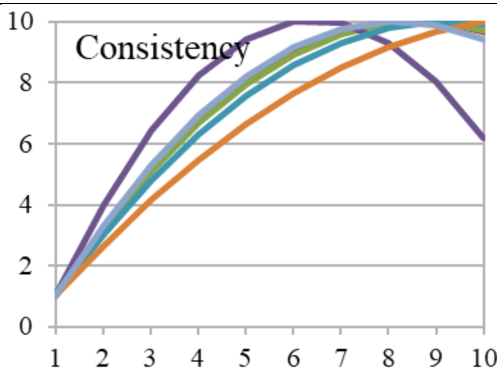
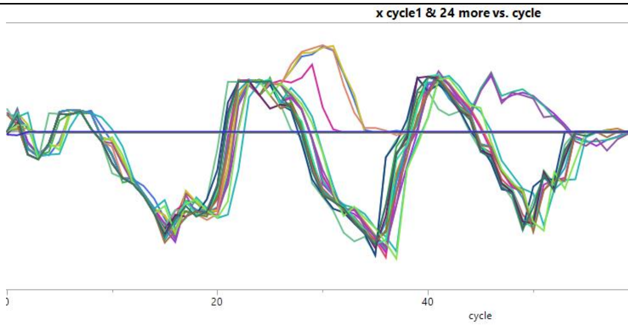
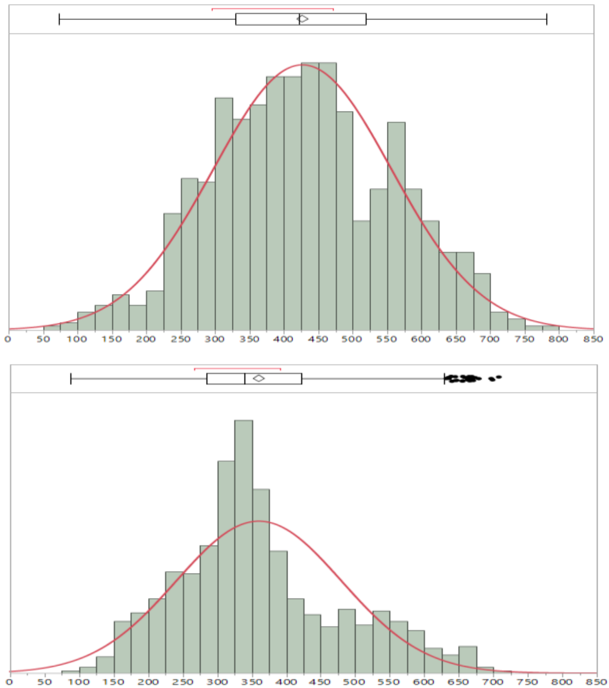
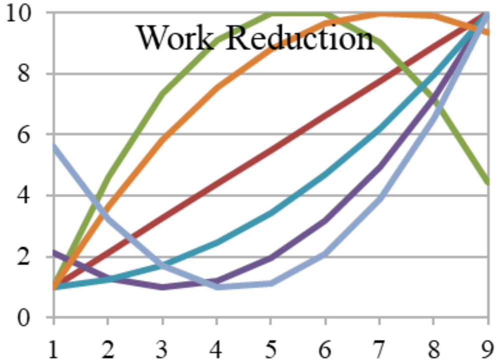
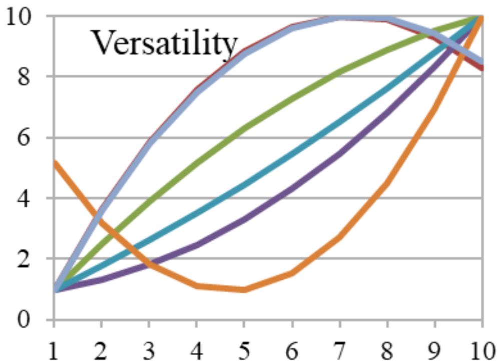



*Figure 15: Consequence start and stop pattern of the process*

| | |
|---|---|
| No robot movement in the complete cycle, effectivity, utilisation of the human-robot collaboration is measurable | <br><br>*Figure 16: Complete cycle mapping with effective work* |
| The evaluation of collaboration space helps to quantify the level of teamwork. Real collaboration can be quantified by the time the human and the robot at the right distance. | <br><br>*Figure 17: Objective evaluation of the human robot collaboration* |
| ***Management priority:***<br>***Consistency*****:** this attribute refers to the degree to which the deployment of the robot improves the consistency of repetitive activities. | <br><br>*Figure 18: Management priority on consistency* |

<table>
<tr><td colspan="2">Detected pattern:</td></tr>
<tr><td>Accuracy, delay, and hurry in the process are visible through the repeated activity. The comparison of cycles shows that instability caused by human movement is quantifiable</td><td><br>Figure 19: Consistency judged based on repeated cycle</td></tr>
<tr><td>Distribution of the minimum distance during the collaboration gives an objective evaluation of the human behaviour. If the human is afraid of the collaboration, then he or she will keep a larger distance.</td><td><br>Figure 20: Distribution of the minimum distance during collaboration</td></tr>
</table>

| | |
|---|---|
| ***Management priority:***<br>***Work load reduction***: this attribute refers to the degree to which the deployment of the robot reduces physical workload for human workers. | <br>*Figure 21: Management priority on work load reduction* |
| ***Detected pattern:*** | |
| Evaluating the workload is possible through the comparison of the before/after situations. Observing human movement before robot implementation helps the better design of the human–robot collaboration process | |
| ***Management priority:***<br>***Versatility:*** this attribute refers to the degree to which the deployment of the robot improves the versatility of application; that is the degree to which the robot can effectively and efficiently be programmed for application to perform a variety of tasks. | <br>*Figure 22: Management priority on versatility* |

***Detected pattern:***

The pattern of the robot's path indicates the movement during the operation as different operations are executed. Every product type has a certain movement pattern and is clearly quantifiable.

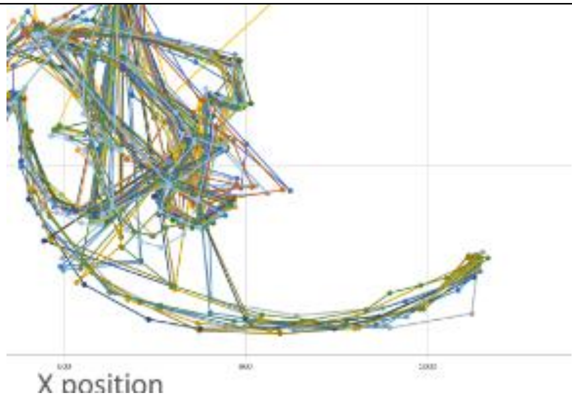



*Figure 23: Pattern of product diversity*

***Management priority:***

***Stability:*** this attribute refers to the degree to which the deployment of the robot ensures stability of performance, eliminating variations or fluctuations associated with humans.

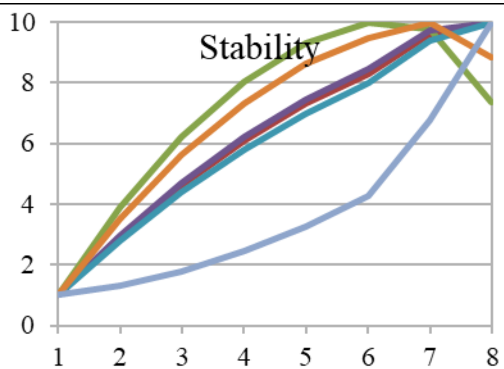
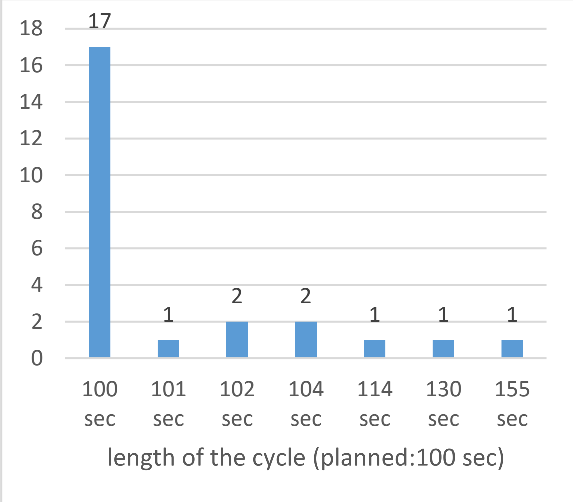
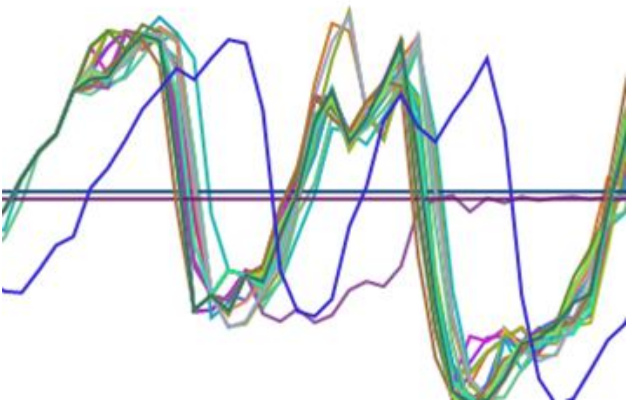



*Figure 24: Management priority on stability*

| | |
|---|---|
| ***Detected pattern:*** | |
| More data detected as in the normal cycle, indicating the instability, delay in process |   *Figure 25: Longer cycle as planned, sign of instability* |
| Postponed data detected indicates delay in robot movement, disturbance within the cycle |  *Figure 26: Delay in process sign of stability/instability* |

***Management priority:***

***Integration:*** this attribute refers to the degree to which the deployment of the robot integrates the process, reducing the required workspace.

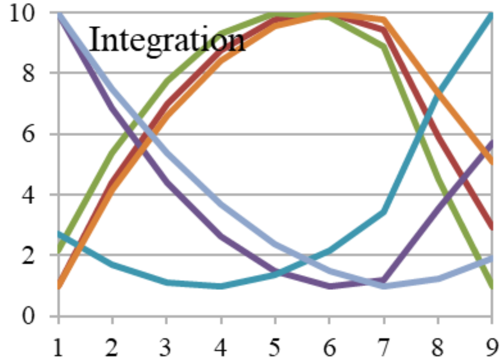



*Figure 27: Management priority on integration*

***Detected pattern:***

The object detection identifies the collaborative space, where the physical interaction appears.

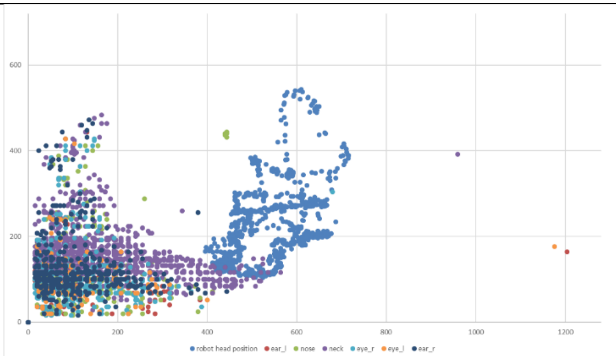



*Figure 28: Physical collaborative space (human and robot)*

The above-mentioned combinations have some overlaps with each other. For example, the pattern of minimum distances is linked to profitability but is also valid to the safety. In the human–robot teamwork, it is essential to connect the management's expectation with measurable evaluation of the real collaboration. The data collected through object detection technology represent the complexity of the human–robot collaboration process.

Connecting the human robot collaborations objective observation to managerial priorities could help the optimal decisions for the represented company.

## 5.3. Confirmation of the propositions

Referring to chapter 4, the propositions, it is observed and judged as follows:

**Hypothesis 1:** Object detection is capable of observing the detail of the human–robot collaboration in industrial environment.

Through the object detection and the collected data set, this hypothesis is **confirmed**.

**Hypothesis 2:** Objective evaluation of the human robot interaction is possible.

Data about the robot, human movement and the relative position makes it possible to evaluate the human robot interaction so this hypothesis is **confirmed.**

**Hypothesis 3:** Data observed in object detection about human robot collaboration show different patterns.

There are several patterns are recognisable, so this hypothesis is **confirmed.**

**Hypothesis 4:** The identified pattern can be linked to management priorities.

The management priorities such as safety, profitability, consistency, versatility, stability, integration could be linked to certain pattern in the human robot collaboration. The work load reduction could not be linked to pattern as it is more a before/after situation to judge, so this hypothesis is **mainly confirmed.**

## 5.4. Further opportunities

Object detection is an evolving technology. It is continuously improving and has new releases that are even faster and more accurate than before. It is worth applying the latest technologies to improve detection quality and speed. Input data quality can be improved through the use of a 3D camera or more cameras, where the positions could be followed more precisely. In addition, a better camera position can affect object detection, especially human movements.

Due to the General Data Protection Regulation, the human face was not in focus this time and could not be evaluated. A further opportunity is to follow the human head based on the recognised information (mimics, head position, eye movement) to evaluate the collaboration. The human body position (face towards to the robot or not) is worth investigating. Objective evaluation of the ergonomic aspects is also possible based on the data. Object detection recognises the human parts (hip, head, legs, hands), so the inconvenient movements in connection with the human–robot collaboration can be assessed.

If more humans work in the collaboration, it makes sense to catch the position of the humans and compare them with the position of the robot. Similarly, when more robots are in the collaboration, it is worth checking how the distance changes.

The object detection technology has the ability to collect a lot of data. More data has more opportunity: evaluation of individual collaboration, long-term behaviour, and change in the collaboration over time holds the possibility to further investigate.

Investigating the before/after situation in collaboration has also potential, the object detection technology capable to evaluate the change occurred.

### 5.4.1. Limitations

The research result has some limitations. As the object detection works based on video, when such a filming is not allowed (see General Data Protection Regulation, GDPR regulation), human robot collaboration cannot be evaluated with the proposed system.

Further limitation is the complexity of the object detection: the influence of the background on images, the changing speed of background environment, light variation, frames/second in a video, the training strategy of the system, the object detection speed, the detection of small and dense objects, the speed of the detectable object, the size change of the object, distance near-far, object only partly on the image, the problem of overlapping objects, the problem of the multiple object tracking, the high computational and memory requirements just to list a few.

A limitation is that the object detection has to be customized for individual case, there is no standard application or program which is „ready to detect”. A limitations is when the organisation want to see such an interaction in the collaboration which is not detectable such as speach, human interaction outside the camera view. Also if managerial priorities so defined which hard to link to detected patterns for example: human relyability or personal traits.