Digital Manufacturing Technology
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UNIVERSAL WISER PUBLISHER

Research Article

An Industry 4.0 Training Framework Addressing 'COVID-19 Type' Disruptions on Manufacturing

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Received: 10 May 2021; **Revised:** 18 June 2021; **Accepted:** 22 September 2021

Abstract: Although digitization in the manufacturing industry has been going on for some years, the recent COVID-19 pandemic helped reveal a number of bottlenecks and challenges that still need to be overcome. Joint ongoing research by a number of European Universities aimed at developing a systematic training framework on Industry 4.0 happened to be performed in the midst of the pandemic. COVID-19 meant that suddenly, internal and external workers of different educational backgrounds and in different roles had to rapidly adapt to new working procedures and environments whilst learning to use new technologies. This disruption helped this research group to generate specifications of a Higher Education Industry 4.0 Training Framework (HEI4.0) that is relevant to foster skills and competencies that make manufacturing more resilient to other possible scenarios requiring social distancing limitations. This paper outlines the details of the research performed and contributes the concept and value of establishing what is termed as the 'flow-cognitive profile chart' of a manufacturing organization to effectively help it in its transition towards digital manufacturing. Based on this concept, the paper passes on to prescribe a HEI4.0 Training Framework intended to guide manufacturing organizations in addressing 'COVID-19 type' manufacturing disruptions that can take place in other future unforeseen circumstances.

***Keywords*:** digital manufacturing, learning styles, supply chain, JIT, Industry 4.0 readiness

Nomenclature

Term	Description
(m:c) index	Manual to cognitive ratio of an activity/process
(M:I) index	Material to Flow ratio
AI	Artificial Intelligence
AMT	Advanced Manufacturing Technology

DOI: https://doi.org/10.37256/dmt.112021921

AGV*n*	Automated Guided Vehicle '*n*'
AR/VR	Augmented Reality/Virtual Reality
c	cognitive
CAD	Computer Aided Design system
CNC	Computer Numerically Controlled
CAx	Computer Aided Technologies such as CAD
DFRA	Design For Remote Assistance
E*n*	Employee '*n*'
'Flow-Cognitive' Profile Chart	A chart representing an organizations processes on a (m:c) versus (M:I) graph
HEI	Higher Education Institute
HEI4.0	Higher Education Industry 4.0 Training Framework
I	Information
ICARUS	Acronym of an EU Erasmus Project - see https://icarusproject.edu.mt/
IDEFx	Integration Definition, a family of systems modelling language
IIOT	Industrial Internet of Things
ILS	Index of Learning Styles
IN*n*	Injection moulding machine '*n*'
IPD	Integrated Product Development
IR*n*	Industrial Robot '*n*'
JIT	Just in time
LNG	Liquified Natural Gas
m	manual
M	Material
MH*n*	Material Handler '*n*'
PD	Product Development
P*n*	Part ''*n*'
SD	Social Distancing
SIPOC	Supplies, Inputs, Process, Outputs and Customers – a tool for process modelling

1. Introduction

When COVID-19 was declared by the World Health Organization (WHO) as a pandemic in March 2020, associated disruptions forced many sectors including manufacturing, to assess, learn and quickly adapt workable solutions that are also applicable to future scenarios. COVID-19 meant that suddenly, internal and external workers of different educational backgrounds and in different roles ranging from shop floor level workers to members of decision-making boards had to rapidly adapt and find means to transit to new working procedures and environments supporting 'social distancing' protocols introduced to flatten the COVID-19 curve [1]. Our research carried out between October 2020 and March 2021 reflects that social distancing (SD) in various forms impacted the manufacturing sector in a number of ways as outlined in Table 1 below. However, the disruptions caused by COVID-19 meant that manufacturing firms had to rapidly adapt or risk bankruptcy. Whilst that a number of manufacturing organizations have as part of the 3rd industrial revolution been exploiting a range of advanced manufacturing technologies (AMT) [2] including digital technologies such as CAD and CNC machinery, many others in particular smaller organizations were still lagging behind even though we are now in the 4th phase of this revolution. For instance, SMEs are known to have a financial, knowledge resource, and technology awareness limitations with respect to the digitization brought about by Industry 4.0 [3]. COVID-19 disruptions also meant that governments had to suddenly channel funds to help firms to digitize more than ever their operations and to re-engineer their processes [EU Horizon 2020 call H2020-SC1-PHE-CORONAVIRUS-2020-2A: Repurposing Of Manufacturing For Vital Medical Supplies And Equipment]. Our interest in addressing such problems goes beyond the specific COVID-19 pandemic issues, as the lessons learned can be applied in other scenarios. Indeed, there exist other unforeseen scenarios that result in major disruptions on manufacturing, such as the 2010 impact across Europe caused by the Icelandic volcano eruption that affected the supply chain and thus the concept of JIT [4] and more recently the Suez Canal blockage caused by the running aground of the Ever Given container ship [5].

Table 1. Impact of SD on manufacturing organizations

Social Distance Measure	Whom it Affected	Impact on Manufacturing Organizations
Closure of schools	Parents	Employees who had nowhere to place their children whilst working suddenly had difficulties in being at work;
Closure of airports /seaports	Employees	The closure of airports/seaports to reduce the transmission of the virus from one employee to another resulted in major supply chain disruptions on manufacturing organizations;
Working from home	Employees	Employees of various grades and levels who handled information related processes could work from home but this meant new and unplanned digitization costs and cybersecurity issues to manufacturing firms;
Physical distancing	Employees	Crowded units/departments had to be organized to have some people working remotely from home and others working on-site; The introduction of mechanisms such as Perspex separators meant additional costs to organizations;
Quarantine periods	Employees	Employees of various grades and levels caught up in quarantine for several days this disturbing planned work;
Use of Sanitizers	Employees	Additional overhead costs;
Use of face masks/visors	Employees	Additional overhead costs; Some employees found it difficult to perform certain tasks with masks/visors on.

Whilst frameworks of how to implement Industry 4.0 [6-9] and other frameworks of how to educate a workforce [10-12] to work in Industry 4.0 environments exist, these are essentially based on the underlying assumption that there is a regular supply and flow of materials, coupled with employees of various grades and levels working on-site. This for instance challenges the concept of lean manufacturing and in particular the JIT [13] concept on which many manufacturing organizations are based. As a matter of fact, Lauren [14] argues that COVID-19 highlighted the need to be able to shift from JIT to Just in Case to help balance priorities. Moreover, the current Industry 4.0 implementation frameworks assume that there is a one size fits all solution, when in reality, different manufacturing organizations have different product development challenges and different human resource skills at their disposal. This situation highlights that there is thus a need for an Industry 4.0 training framework addressing the needs of specific manufacturing organizations to help them cope better with impacts arising from unforeseen circumstances such as social distancing situations and supply chain [15] disruptions.

1.1 *Overall research approach*

The research approach adopted in this work is outlined in Figure 1. Commencing from acknowledging (Step 1) that manufacturing taking place under disrupted operating conditions due to unforeseen scenarios gives rise to problems, in Step 2 we pass on to verify and understand the extent of this problem by [A] analyzing through a survey and a literature review, the actual impacts on manufacturing and similarly [B] analyzing through a survey and a literature review, the typical learning styles and methods of personnel involved in these disruptions. This understanding gave rise to the hypothesis (Step 3) that exploiting Industry 4.0 enablers to address the needs of specific organizations will help offset disruptions encountered in such unforeseen scenarios.

This hypothesis, however, gave rise to a specific research problem (Step 4) i.e. how can we synthesize an HEI training framework that addresses the specific needs of a manufacturing organization’s specific disruptions? Indeed, this step is the main focus of the research reported in this paper. Following the generation of a specific HEI4.0 Training Framework, as outlined, this needs to be evaluated (Step 5) by the implementation to help address the problems arising from unforeseen manufacturing scenarios.

In our research, higher education has been considered to consist of education of current HEI students as well as past HEI graduates that need to catch up with Industry 4.0 concepts and principles. This paper now proceeds from Step 2 onwards to disclose the research performed and the solution developed.

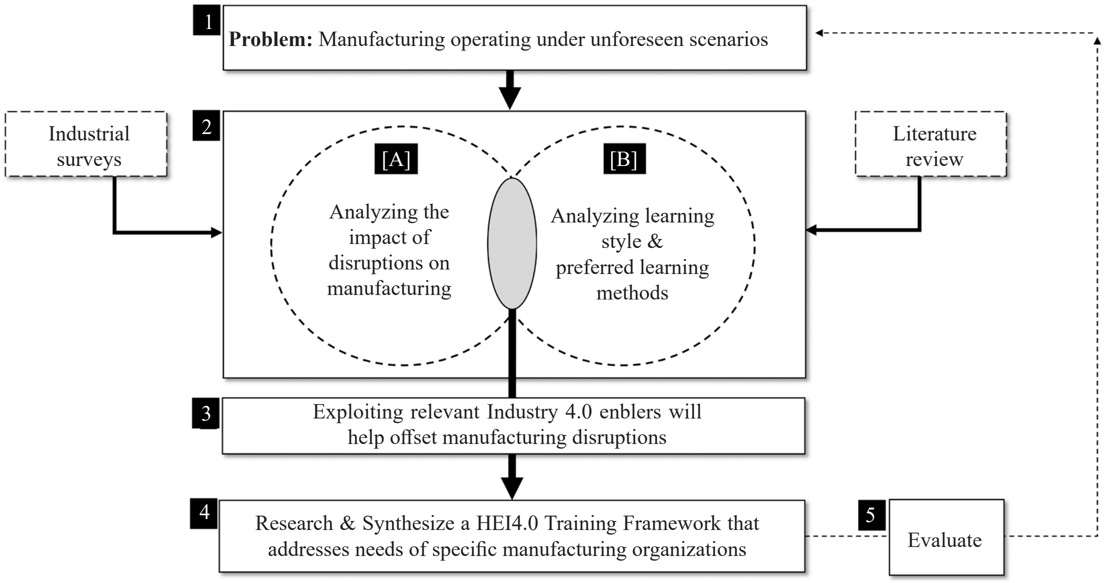


Figure 1. Research approach adopted from Duffy, A. H., & O'Donnell [16]

2. Product development disruption sources during COVID-19

As outlined in Step 2 of our research approach (Figure 1), we performed a literature review to establish the extent of unforeseen scenarios on manufacturing activities as well as on the different approaches to training in Industry 4.0, both of these already outlined in our introduction to this paper. However, as part of Step 2, we also performed separate surveys, one on COVID-19 impacts and another one on industry 4.0 training approaches and learner needs. Building upon previous work performed by the authors [17], in designing our research surveys, we based our understanding of what takes place in manufacturing organizations using the Integrated Product Development (IPD) Framework [18]. Hence, our survey was based on identifying issues with both material and information flows during product development, with the main survey questions focusing upon:

- design
- fabrication/production
- sales/marketing.

This survey (Step 2A of the research approach) was performed during the period October 2020 and March 2021 with small (< 10 employees) and large (> 249 employees) organizations involved in a range of sectors including pharmaceutical, biomedical, food/beverage, rubbers/plastics, electronics, automotive, cosmetic packaging. Due to COVID restrictions, data was collected by online structured interviews with key results outlined below.

As indicated in Figure 2, the design processes which tend to be information rather than material-based had hardly any impact. On the other hand, supply chain related processes which by default involve more material flow such as raw materials was as one anticipates, significantly impacted. As a result of this impact, this consequence [19] also propagated onto fabrication/production processes. This impact was further propagated to the delivery of products as reflected by the outgoing finished goods. A closer look at the data obtained (Figure 3) from the structured interview survey helps also identify trends in the main source of the impact. For instance, for incoming raw materials, the main source reported is 'supply chain difficulties' due to restrictions imposed on airports and seaports. On the other hand, during fabrication/production, the main sources of problems were actually a hybrid of reasons, including lack of raw materials due to supply chain difficulties as well as lack of human resources due to social distancing restrictions (e.g. staff in quarantine), combined with a drop in product demand. Whilst that as presented, the analysis snapshot is generalized, in reality, exceptions were encountered such as for example biomedical and pharmaceutical related organizations actually reported an increase in demand of certain product portfolios. This clearly indicates that whilst certain issues are common, nevertheless different organizations encounter different challenges and thus require different solutions to cope with such disruptions.

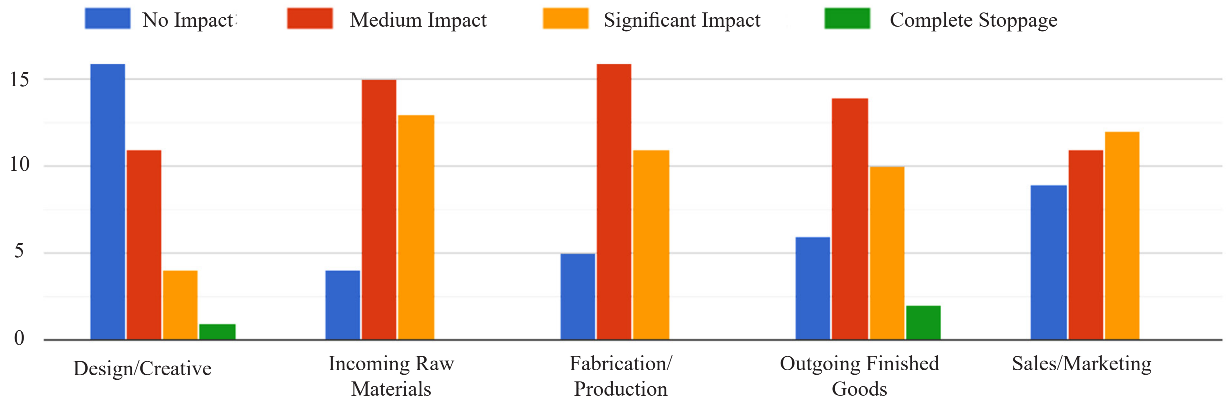


Figure 2. Relative impact of COVID-19 restrictions on product development

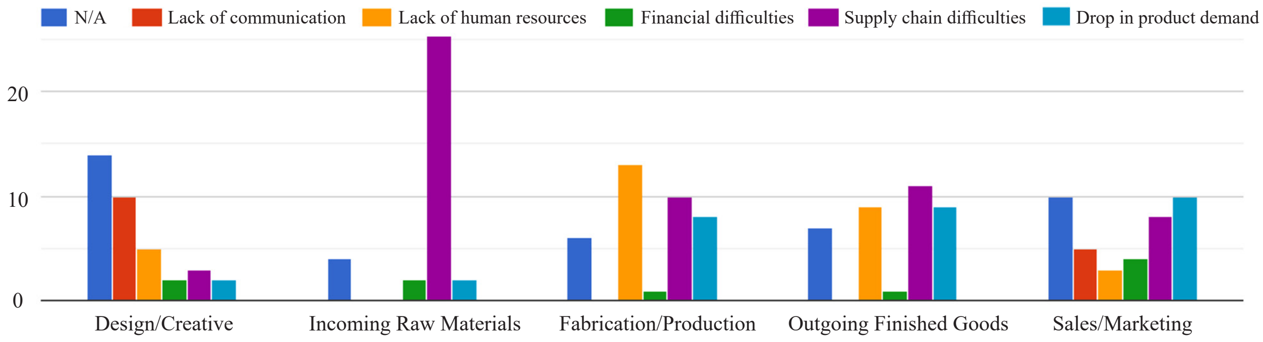


Figure 3. Source of COVID-19 impacts on product development

2.1 *COVID-19 impact survey results*

A clear conclusion arising from the survey (research Step 2A) carried out is that activities (e.g. testing) during product development that highly depend on human manual interactions and utilization of non-digital equipment (e.g. lab facilities) were the source of major impacts on manufacturing. Our survey also indicates that processes within manufacturing organizations that had a high manual: cognitive ratio were critical sources of disruptions. From the data collected, it was evident that major impacts (Figure 4) were mainly encountered where the material flow was involved as this many times involved the interaction of both people and machines, typically on the shop floor level. Fever disruptions took place where mainly information flow was concerned, such as the board room level decision making that could still take place via online meetings. In our research, we even encountered situations where during the peak of the pandemic, senior managers including CEOs were also managing big organizations from home. Nevertheless, other processes predominantly depending on information flow (back office, middle management, board level) still experienced some impact as social distancing meant that work in an office was restricted to a number of maximum people. These disruptions were however more easily overcome as through the provision of hardware and cybersecurity solutions, such employees could after a couple of days resort to working remotely from home using online collaboration platforms such as Microsoft Teams and Zoom [20].

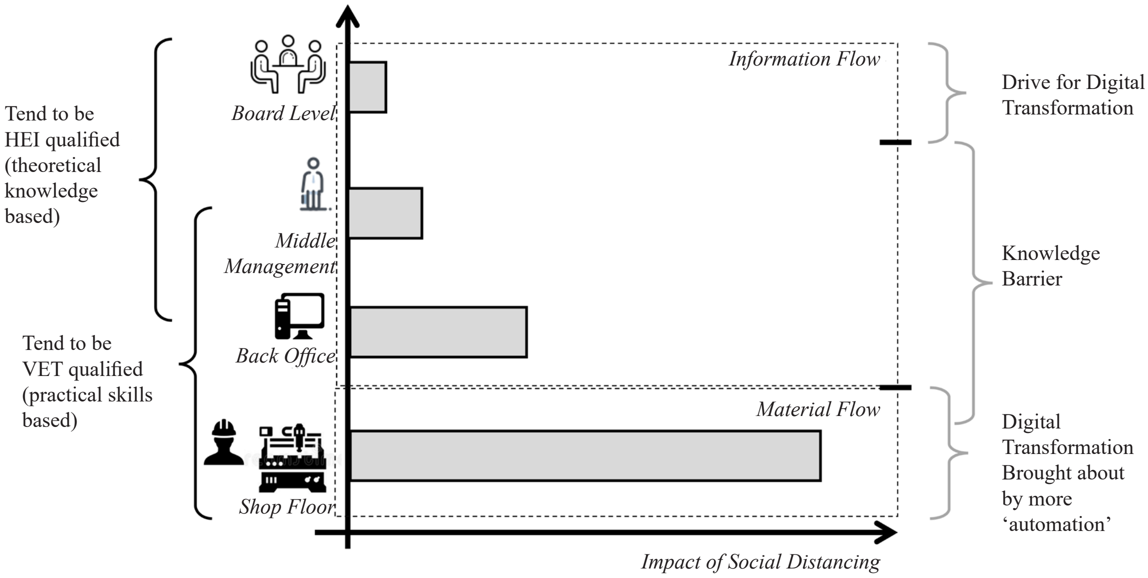


Figure 4. Overall disruptions on manufacturing due to social distancing

A noticeable fact is that decisions made by senior and middle management associated with pushing for digital transformations in lower levels, such as the shop floor, affected employees that had mainly a manual skills background and who were mainly involved in processes related to material flow, and not sufficiently trained in a range of digital enablers. However, product development processes that involved a mix of information and material flow, required further analysis to understand what was happening, as discussed next.

2.1.1 *The Material: Information (M:I) flow index*

Our research indicates that impact level on manufacturing was higher on product development processes with a high (>1) Material: Information (M:I) ratio. For instance, milling a part on a conventional milling machine has an M:I > 1. On the other hand, designing a part has an M:I = 0 as during design, only information is required. The tendency that processes with an M:I < 1 can take place remotely is higher:

2.1.2 *The Manual:Cognitive (m:c) index*

Another phenomenon involved is the mix of cognitive (c) and manual (m) input required to cause a product development process transformation. For example, the information (I = drawings) required to mill a part (M = raw material) on a conventional and also on a CNC milling machine are similar. However, the cognitive (c) input provided by a CNC part programmer to a CNC milling process is higher when compared to the conventional milling (Figure 5) process.

On the other hand, our research indicated that mainly manual (m) activities such as loading machine tools could still take place by human operators as long as the material was available and as long as social distancing rules were respected. However, when for instance a milling machine operator who had substantial knowledge and experience (cognitive) on how to mill different parts was unavailable at work due to quarantine, the manufacturing organization still suffered a degree of disruption. At the same time, processes that are mainly cognitive (c) in nature (e.g. product design, process planning) were least impacted by SD limitations as these were again mainly related to information (I) flow, with the cognitive actors (human beings) more able to resort to working remotely.

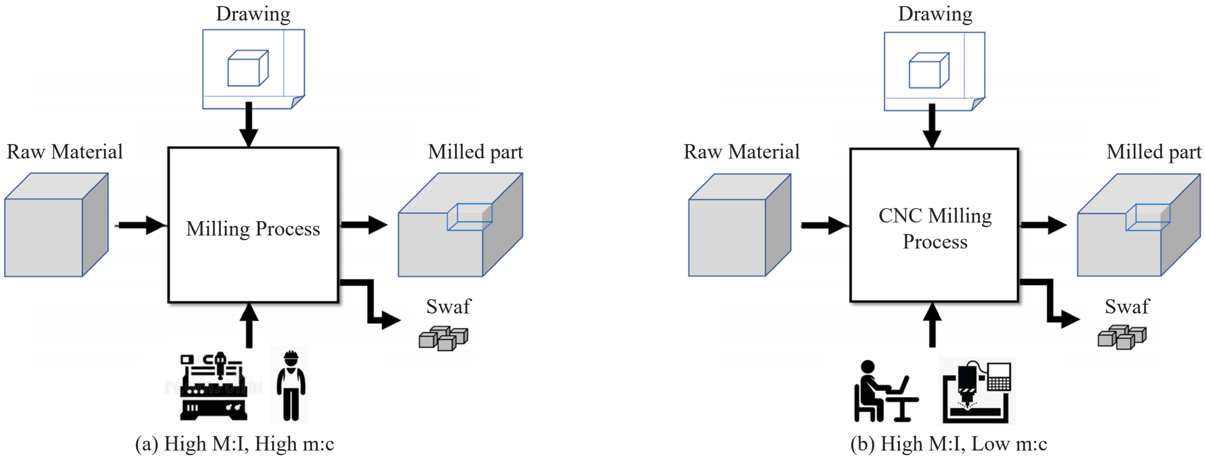


Figure 5. IDEF model of (a) traditional and (b) CNC milling processes

2.1.3 *Disruptions depend on the combination of (M:I) and (m:c) index values*

As argued in this section, disruptions in a specific manufacturing organization thus depend on the combination of (M:I) and (m:c) indices related to its product development processes. For example, the m:c ratio (>1) of manual and cognitive skills required for joining two components (e.g. M = mild steel) using manual arc welding is very different from the m:c ratio (<1) of using a robotic welding process to join the same two components. The combinations of (M:I) and (m:c) index values can thus be used to generate a 'flow-cognitive profile chart' (Figure 6) of a specific organization. Our analysis revealed that the area above the diagonal is indicative of product development processes that fall within a critical zone with respect to suffering disruptions arising from social distancing and supply chain restrictions.

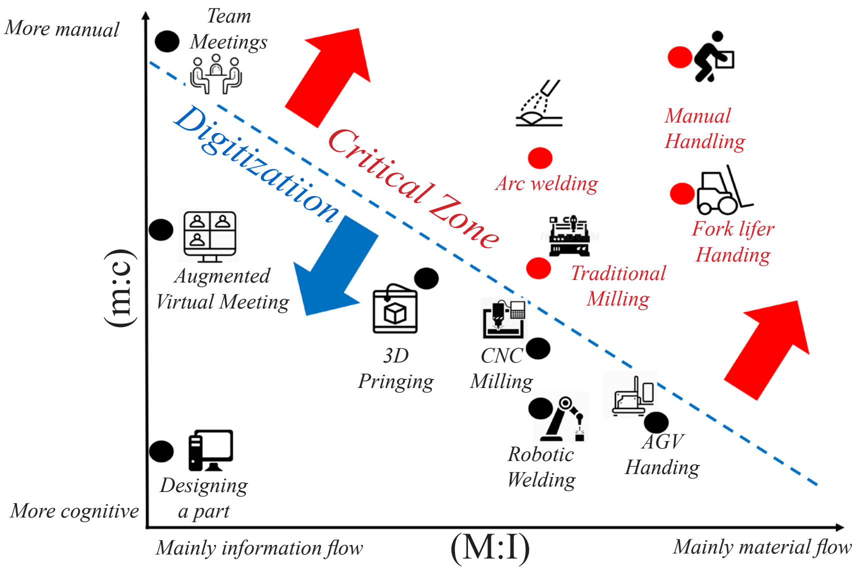


Figure 6. Typical organization 'flow-cognitive' profile chart

On the other hand, those processes that employ a high level of digitization, fall below the diagonal and thus tend to be less sensitive to material and physical (e.g. social distancing) disruptions. Thus, through such a 'flow-cognitive profile chart', an organization would be able to identify and introduce relevant Industry 4.0 enablers that will shift its product development capability from one that is in the critical zone to a relatively safer zone beneath the diagonal. This would however require the acquisition of both technological infrastructure as well as the upgrading of employees with relevant digital skills.

3. Survey of Industry 4.0 training needs & challenges

Based on Step 2B of our research approach (Figure 1), to understand the impact of skills required by the introduction of new digital technologies, a training needs survey was performed as part of our ICARUS[https://icarusproject.edu.mt/erasmus/] Erasmus+ project during the period February 2020 and October 2020 with a sample both HEI trainers and learners across eight EU countries, namely Germany, Italy, Malta, Portugal, Romania, Spain, Sweden and Switzerland. After discussions amongst the ICARUS partners, it was decided that the best approach to collect the required information from relevant stakeholders would be to utilize an online survey. This type of data collection method allowed the consortium to reach out to a wide-ranging audience and ask about the different aspects required for developing an Industry 4.0 training toolbox. This also enabled all partners to utilize the same format and questions for homogeneity of the data being collected, which also facilitated data analysis.

Table 2. Survey target audience

Target Group	Type	Sample Size
TG1	Trainers	10 – 15 per ICARUS Partner
TG2	Past HEI learners	10 – 15 per ICARUS Partner
TG3	Current HEI learners	25 – 30 per ICARUS Partner

Irrespective of COVID-19 disruptions, the survey was intended to mainly understand amongst the defined target audience (Table 2) besides other issues, the following:

a. *What skills and knowledge are required to bridge the Industry 4.0 gap amongst the different learning gro*ups?

The focus here was (i) to establish the knowledge and skill aspects required for the development and implementation of Industry 4.0 solutions and (ii) establish knowledge aspects related to industrial readiness, key enablers, and barriers, operator and sustainability issues;

b. *What are the learning methods and styles preferred by the different learning groups?*

The focus here was to understand how to best deliver the training content developed. Learning methods are the pedagogic approaches that can be utilized for effective knowledge transfer. On the other hand, learners are known to exhibit various learning styles ranging from visual to auditory to kinesthetic learners. Hence, the results would also enable us understanding how an Industry 4.0 training toolbox can cater for different learning styles.

3.1 *Training needs survey results*

3.1.1 *Industry 4.0 implementation knowledge*

To understand the training requirements, and develop the specifications, the respondents were asked about the specific training areas where they needed to gain knowledge. Respondents were asked to rate between 1 (Not knowledgeable) and 5 (Very knowledgeable) a number of Industry 4.0 enablers. The aim was to gain an indication of a number of areas where a knowledge gap exists. Hence any training material/framework being developed must address this knowledge gap.

As can be seen in Table 3 concerning specific Industry 4.0 enablers, the survey indicated the following trends. Respondents were above average knowledgeable in the fields of additive manufacturing and 3D printing, Industrial Internet of Things (IIoT), Augmented and Virtual Reality (AR/VR), and simulation in manufacturing applications. In the area of cloud computing, collaborative robotics, and big data analytics, respondents were less knowledgeable and in general, had an average response tending towards the less knowledgeable. In the areas of data integration and cybersecurity, a clear trend is identifiable that the majority of users felt they lacked knowledge in these areas. It is clear from these results that there is a need to provide knowledge and address the skills gap in the areas relating to data analytics and information exchange. Data analysis is a central and critical link in the implementation of cyber-physical systems, hence it can be concluded that this skills gap is one of the main barriers for the implementation of Industry 4.0 and has to be addressed in the ICARUS training toolbox.

Table 3. Knowledge of Industry 4.0 enablers

	Average (1-5)
Additive Manufacturing	3.43
IIoT	3.27
Augmented & Virtual Reality	3.27
Simulation	3.19
Cloud Computing	2.95
Autonomous & Collaboration Robotics	2.93
Big Data Analytics	2.58
Horizontal and Vertical Data Integration	2.40
Cybersecurity	2.35

3.1.2 *Industry 4.0 organizational knowledge*

In contrast to 'implementation knowledge' it was immediately noticeable that respondents had less knowledge concerning the implementation of Industry 4.0 within organizations and the respective social aspects and challenges. The survey indicated the respondents only had average knowledge in areas relating to workers, change management, training and sustainability, and ethics in Industry 4.0. In correlation to the implementation knowledge, respondents showed a similar lack of knowledge in cybersecurity issues which would affect an Industry 4.0 organization and how these would be tackled.

It is therefore critical that training content would not only tackle the technological knowledge required for the implementation of Industry 4.0 enablers but would also be complemented with knowledge about how to drive digital transformation and change within the organization. This knowledge has to address various aspects of an organization, including the ethical considerations which these technologies bring with respect to workers and employees, to new operator training concepts. Training of the existing workforce is therefore required to support a company's transition and change towards Industry 4.0 with the aim of remaining sustainable in the long term as well as dealing with new and evolving cyber security threats which could threaten an organization.

Table 4. Knowledge of Industry 4.0 organization & social aspects

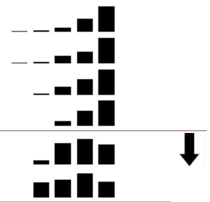
	Average (1-5)	1 - - - 5
Digital Transformation in Industry 4.0	3.14	
Work 4.0 and Operator 4.0	2.92	
Change management in Industry 4.0	2.91	
Training concepts for Industry 4.0	2.81	
Sustainability and Ethics in Industry 4.0	2.79	
Cyber Security Issue in Industry 4.0	2.32	

3.1.3 *Preferred learning methods*

As previously argued, an effective training methodology must be established in order to transfer the knowledge in Industry 4.0 implementation and organizational knowledge. Respondents were therefore asked about the methods which they found most effective when learning. Our results indicate that the preferred learning method was practical/ laboratory-based learning, with only a few exceptions not preferring this type of learning method. As will be discussed in the next section, this correlates with the preferred learning styles, which sees respondents prefer an active versus reflective approach to learning. Also, notwithstanding the increased digitization in our daily lives, with respect to the learning methods listed in Table 5, it was clear that face-to-face learning remains by far the preferred approach to learning especially when compared with respect to online and e-Learning. In fact, respondents clearly indicated that online collaborative work was the least preferred. Whilst this data was collected before the peak of the COVID-19 pandemic, which saw a widespread utilization and appreciation of online learning [21], it is clear that given a choice, respondents would prefer a more active and dynamic approach to learning. Whilst e-Learning satisfies the needs of some respondents it does not appeal to all, and hence this needs to be taken into consideration when developing training methods and material as part of the ICARUS training toolbox.

Table 5. Preferred learning methods

	Average (1-5)	1 - - - 5
Laboratory Work	4.34	
Face-to-Face Lecturer	4.30	
Case Studies	4.18	
Face-to-Face Group Work	4.16	
E-Learning	3.52	
Online Collaborative Work	3.41	



3.1.4 *Preferred learning styles*

The final aim was to understand the different learning styles of the respondents. The method used was based on the Index of Learning Styles [22]. The ILS questionnaire (40 questions) results create a profile that indicates a learner's preferences. A person's learning style profile provides an indication of learning strengths and possible tendencies. According to Felder and Silverman, the model has four dimensions of learning styles. As indicated in Figure 7, each of the four scales of the index of learning styles has two opposite preferences. In line with the results obtained from the learning method questions, it is apparent that the respondents preferred an active, sensing, and visual learning approach. Active learners tend to retain and understand information best by doing something active with it, e.g. discussing or applying it, for example in a laboratory or demonstration session. Learners who prefer a sensing approach remember and understand information best if they can see how it connects to the real world, e.g. through case studies. Hence it is important that to achieve a better learning experience to not only provide knowledge and content about Industry 4.0 enablers and technology but complement this with examples of how it is implemented within industrial scenarios. Also, since the respondents greatly preferred visual styles, it is important that the training material uses diagrams, sketches, schematics, photographs, flow charts, or any other visual representation of course material.

Finally, whilst not exhibiting a strong preference, respondents preferred a sequential presentation of knowledge which allows them to gain understanding in linear steps, with each step following logically from the previous one. That said, it is also important for the ICARUS training toolbox to allow the possibility for learners who prefer a more unstructured approach to learn, to be able to access relevant information and knowledge on request.

It becomes apparent from the analysis of the training needs survey results, that the ICARUS training toolbox must provide a modular approach to learning which allows a degree of customizability depending on the specific needs of a learner. This should take into consideration the specific knowledge which needs to be targeted as well as the preferred learning methods and styles. Also, an active means of how to demonstrate and explain the concepts and enablers of Industry 4.0 is required to complement the training content, which would allow the learner to experience, visualize and augment their understanding of the theoretical content. Thus, these results collectively provide the basis for the development of a relevant HEI Industry 4.0 training framework upon which to base the implementation of the 'ICARUS training toolbox'.

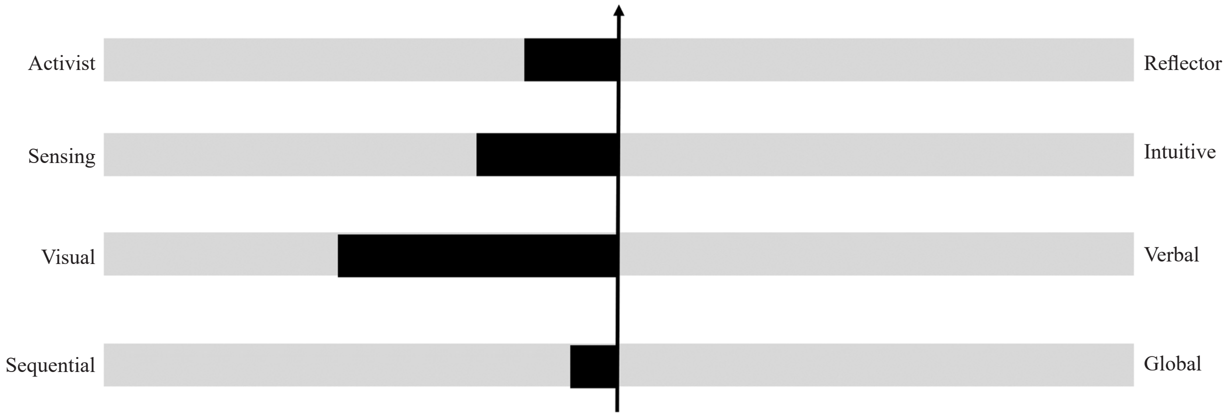


Figure 7. Preferred learning styles

4. A prescribed Industry 4.0 training framework for 'COVID-19' type disruptions

The current state of the art and survey outlined earlier indicate that different manufacturing organizations require different solutions to cope with disruptions arising from unforeseen scenarios such as SD restrictions. This means that the infrastructure of an organization and as a consequence its related human resources, need to be improved to make them more resilient to such disruptions. Building upon arguments previously presented and in correlation with Step 4 of our research approach (Figure 1), we have thus developed the framework outlined in Figure 8 intended to allow manufacturing organizations to cope with 'COVID-19' type disruptions specific to them.

4.1 *Design for Remote Assistance (DFRA) framework*

Frames (0), (1), (2), and (3) are collectively aimed at re-designing the product development processes to make them more aligned with being able to be operated remotely. Hence, these sub-frames are collected termed the 'Design for Remote Assistance (DFRA)' framework. DFRA is concerned with designing a specific Industry 4.0 environment for the needs of a specific organization.

Frame 0 - Disruptions Alert Level Assessment: Through Frame 0, manufacturing organizations can initiate a study to perform 'what-if' analysis to adequately plan and if necessary implement contingency plans. Here, users of the framework can explore scenarios based on possible restrictions used in past alert level cases to understand how these will impact their manufacturing organization if governments had to impose such restrictions. Such alert level cases include those related to for instance health [23], volcanic eruptions [24], and terrorism [25]. For instance, in January 2020, there were no social distancing restrictions in place although WHO announced mysterious pneumonia in China that had already impacted 59 cases. Later, in March 2020, WHO declared COVID-19 as a pandemic this resulting in new restrictions levels. Thus, Frame 0 is concerned with modeling and defining timelines and restriction levels to be used in the 'what-if' study.

Frame 1 - Model PD Processes: To be able to foresee possible impacts arising from different alert level scenarios, an organization needs to model the specific processes involved in its different product development phases. This modeling can be achieved using tools such as IDEFx [26] as well as SIPOC [27]. For organizations that make use of a digital twin [28] approach, Frame 1 can indeed be represented within such a twin model. When the Frame 1 model already exists, the whole DFRA exercise can skip from Frame 0 to 2.

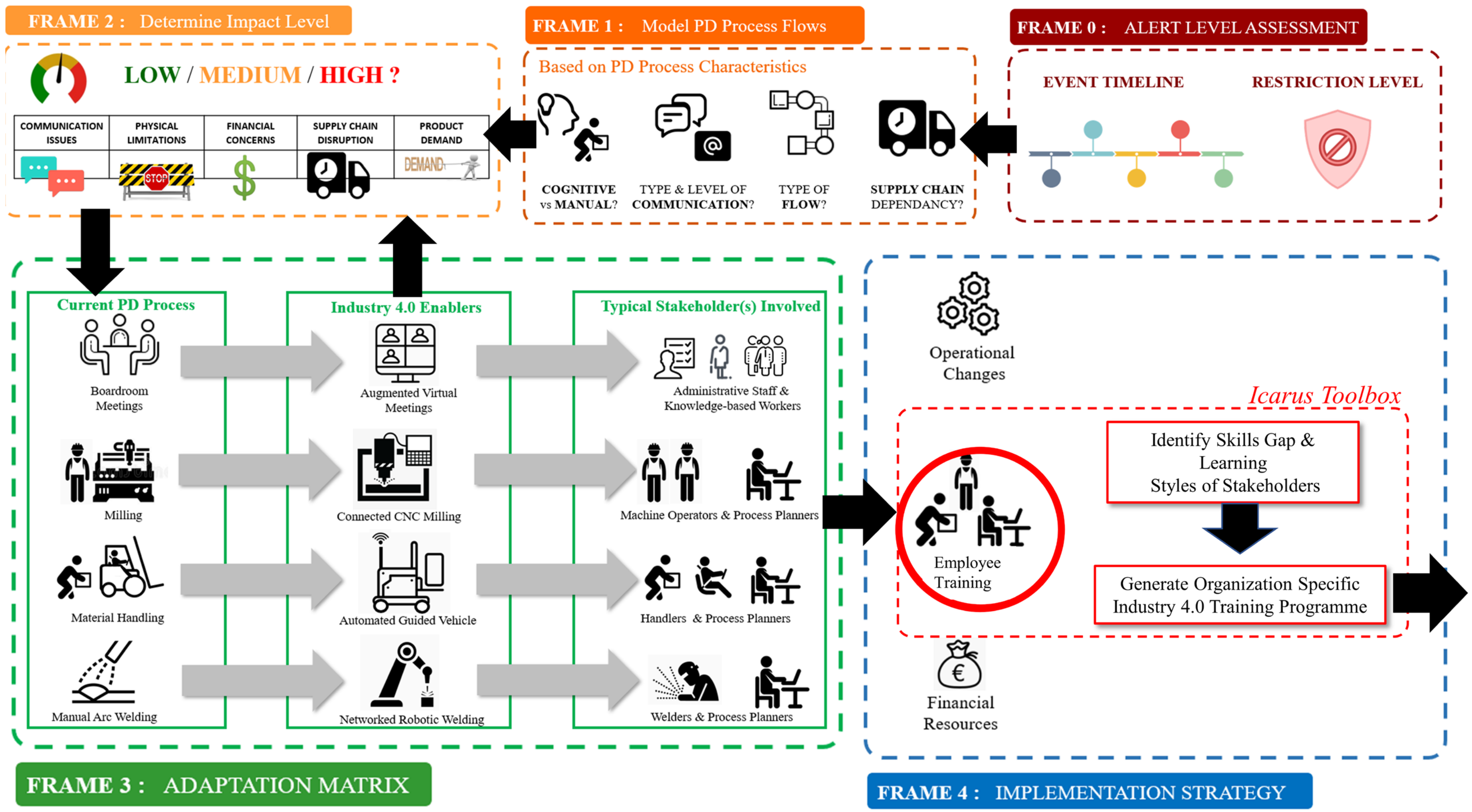


Figure 8. Prescribed HEI Industry 4.0 training framework

Frame 2 - Determine Critical Processes: Once the organization's process flow models are available, the next step is to establish (M:I) as well as (m:c) index values to generate the 'Flow-Cognitive' Profile Chart (similar to that in Figure 6) specific for that organization. Through this profile chart, the organization will be able to determine which PD processes are within the critical zone and hence which are sensitive to unforeseen scenarios such as SD restrictions.

Frame 3 - Adaptation Matrix: Building upon Step 3 of our research approach (Figure 1), once critical processes are identified, decision-makers need to be provided with a set of possible Industry 4.0 solution enablers (Figure 9) that can improve the organization's (M:I) and (m:c) profile. The goal here is to identify (by iterations back to Frame 2), a set of alternative Industry 4.0 enablers that would make the organization's overall Flow-Cognitive profile more resilient to SD and supply chain restrictions, i.e. enablers that are not within the critical zone. At the same time, the stakeholders associated with the critical processes are identified and considered as candidates requiring training on the specific Industry 4.0 enablers being recommended for that organization. Similar to Frame 1, the enablers selected in Frame 3 can be embedded within a digital twin model of the organization's manufacturing system. Thus, by exploring alternative enablers in such a digital model, different impacts can be foreseen via iterations to Frame 2, before a final solution that is considered sufficiently resilient to SD disruptions is selected for implementation as part of Frame 4 and hence specific training is required established.

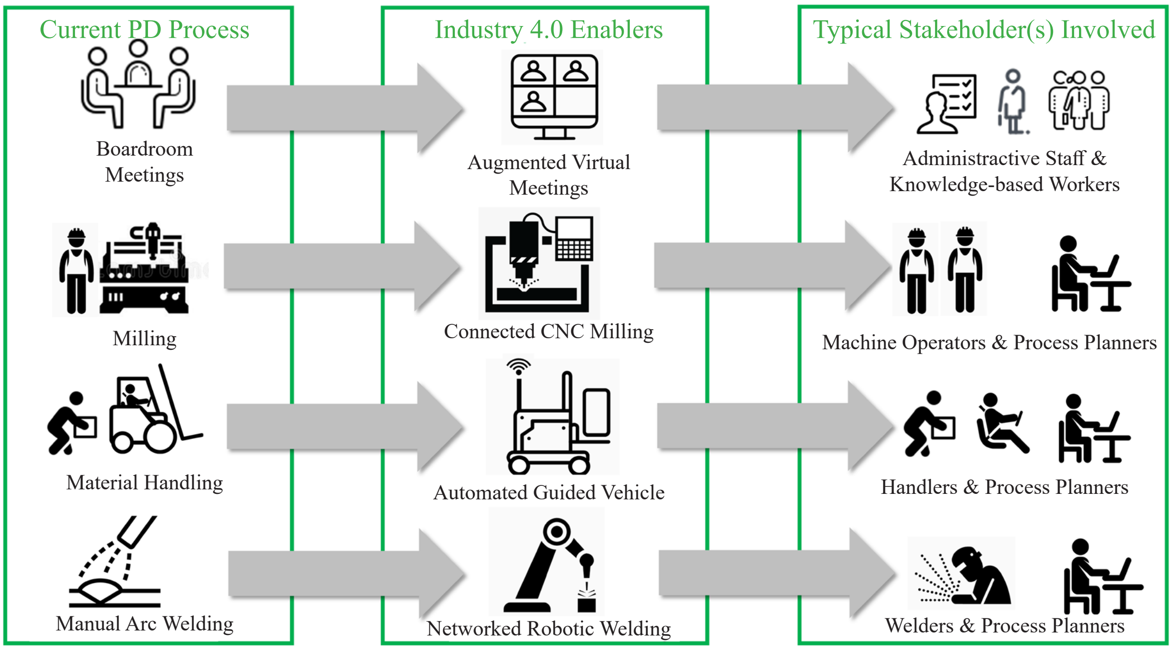


Figure 9. Typical Industry 4.0 technologies that change an organization's (M:I) & (m:c)' profile

4.2 *Implementation strategy frame: Personnel training*

Once a solution fostering remote manufacturing capability is established through the DFRA Framework, **Frame 4 – Implementation Strategy** responsible for realizing the solution designed is invoked. With Industry 4.0 enablers selected and stakeholders that require training to catch up with the solutions chosen identified, an implementation strategy by the manufacturing organization can be put in place. As outlined in Figure 8, Frame 4 essentially encompasses the Operational Changes to be made to the product development processes, Employee Training required for the selected enablers as well as a strategy for securing the necessary financial resources to implement the strategy. For the scope of this paper, we will focus on Frame 4's Employee Training aspect.

4.2.1 *ICARUS Industry 4.0 employee training toolbox*

The results emerging from the previous frames and in particular Frame 3, The Adaptation Matrix provide an outline of the type of personnel requiring training on the specific Industry 4.0 enablers being recommended for that organization, as well as the product development changes required. For example, if Frame 2 reveals a high impact on material flow due to supply chain disruptions, the manufacturing firm would benefit from changing the JIT inventory to cope with an improved buffer of materials/supplies. Hence the ICARUS project generated a 'toolbox' with a set of digital training resources (partially disclosed in Table 6) covering different Industry 4.0 topics that can be applied via different training methods. The toolbox is as its name implies, just a toolbox with a set of knowledge resources on different Industry 4.0 enablers. However, it also incorporates the related training method(s) that can be used to effectively transfer knowledge to employees. Furthermore, the toolbox becomes a powerful enabler to fostering digital manufacturing, when the set of training sources selected for employees of specific organizations, is based on the results of Frame 3.

Table 6. Industry 4.0 training resources content & methods

Impact	Training Content Required	Training Method(s)
Medium / High Impact on Strategic Communications/ Information Flow	• Collaborative Team Platforms; • Cloud Services; • Cyber-Security; • Data Integration.	Face-to-Face Group work complemented by e-Learning training material and/or online collaborative work.
Medium / High Impact on Quality Control Communications/ Information Flow	• Sensors/Data Collection; • Big Data ; • Machine Learning & AI; • Cyber-Security.	Face-to-face teaching, complemented by e-Learning, Demonstration and Case-Studies
Medium / High Impact on External Material Flow/Supply Chain	• Managing Supply Chain; • Digital Supply Chain; • Just in Case (vs Just In Time); • Limitations of Lean & Agile.	Face-to-face teaching, complemented by e-Learning, and Case-Studies
Medium / High Impact on Internal Material Flow	• Digital alternatives such as AGV, Drones; • Industrial and Collaborative Robotics.	Face-to-face teaching, complemented by e-Learning, Demonstration and Case-Studies
Medium / High Impact on Product Demand	• Creativity & Innovation; • Repurposing of Manufacturing Processes.	Face-to-Face Group work complemented by e-Learning training material and/or online collaborative work
Medium / High Impact due to Physical Limitations (SD)	• Augmented/Virtual Reality; • Industrial Internet of Things.	Blended learning, Demonstration and Case-Studies and digital twin Exploration

4.3 *Prototype implementation & evaluation*

For research experimental purposes, the HEI 4.0 Training Approach Framework has been implemented as a prototype tool in the form of a spreadsheet (available at: https://tinyurl.com/84yb6hfx) with complex relationships that map inputs and outputs from one frame to another. In the long term, the actual framework can be embedded as part of a digital twin to enhance project-based engineering education. The key difference between the work reported in this paper and work carried out by for instance Nikolaev et al. [29] is that through the prescribed HEI 4.0 Training Approach Framework, users can proactively foresee the impacts of alternative alert levels on current production as well as be guided to the Industry 4.0 enablers and associated training required to improve an organization's resilience to SD and supply chain disruptions. For evaluation purposes (Step 5 of our research approach), a case study of how the DFRA framework can be exploited leading to the identification of relevant training required was developed and demonstrated to three engineers/practitioners in the industry as well as three peer experts from other academic institutions for their feedback and impressions.

One may understandably argue if this evaluation approach is sufficient. However, at times of a crisis, engaging in exhaustive quantitative evaluation is not always possible and is entirely the best approach. This is because swiftly reacting and disseminating relevant knowledge and innovative approaches, without compromising quality is equally important. This is applicable, as for instance argued by Huber et al. [30] even to the contribution of this research work in the field of education. Clearly, it is also not possible to compare the impact of the envisaged solution with a disruption in a real manufacturing organization, if disruptions are something that occurs randomly and is being avoided in practice.

So, whilst the sample of evaluators involved is not exhaustive, the overall positive results obtained and the qualitative feedback provided via this case study and consultation are considered an overall good indicator of the prescribed framework's value.

4.3.1 *Case study: Disruptions due to gas leak in industrial zone*

In essence, the case study consists of a company ABC Ltd producing thermoplastic toys assembled from different parts (Figure 10). The company is located 4 km away from an electric power generation plant supplied with Liquified Natural Gas (LNG). Company ABC Ltd wants to explore how it can prepare for disruptions should there be a leak of LNG and traffic flows within a 5 km radius have been limited and employees are expected to stay away. The case study focuses on part of the process where a number of toy parts are molded and assembled (Figure 13). It assumes that the gas has created a toxic environment within the 5 km radius, yet operations can still take place without causing fire hazards.

Using Frame 0, company ABC defines (Figure 11) the restriction level as high (level 3) and time-line as possible (LP). To establish the company's flow-cognitive profile, the different activities involved are defined via Frame 1 (Figure 11) as to whether they are physical (e.g. material handling) or equally physical and cognitive (e.g. assembly of parts), etc. Incoming material is handled by a fork lifter (MH1) operated by employee E1. The two PLC-based injection molding machines involved (IN1 and IN2) are manned by employees E2 and E3 respectively (Figure 13).

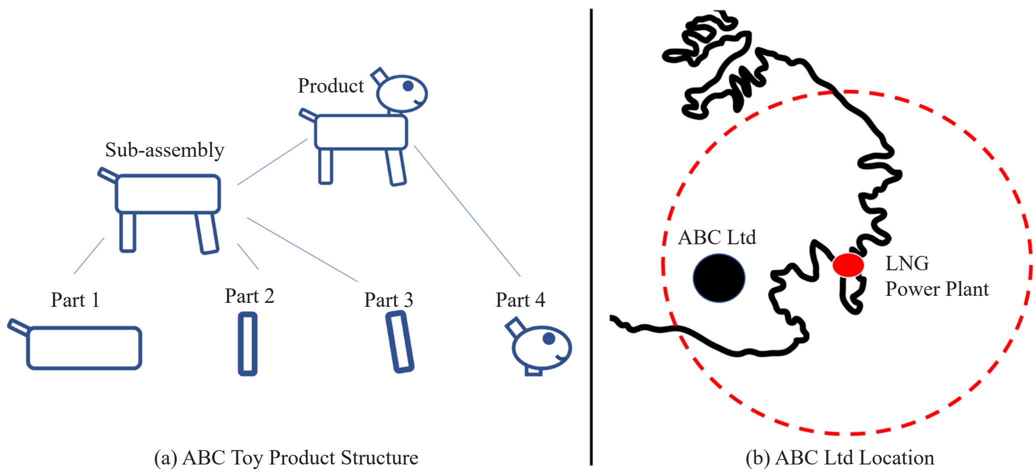


Figure 10. ABC Ltd Case study scenario

The parts produced P1 and P2 are handled by employee E4 and taken in batches to the assembly department where employees E5 and E6 assemble the parts to product sub-assembly P3. Frame 0 and 1 inputs generate codes reflecting the case study scenario which lead to the inference of the likely impacts in Frame 2.

Through Frame 3 (Figure 12), the framework allows alternative, recommended adaptations for the different Frame 2 inferred codes to be explored and their relative perceived effectiveness, operational impact, and human resources impact to be compared to the original process flow model. Based on the exploration analysis performed, ABC Ltd considered adapting the set of Industry 4.0 enablers schematically illustrated in Figure 13 as this helps improve its 'flow-cognitive profile'.

In this solution, fork lifter MH1 is replaced with a semi-autonomous AGV1, implying that employee E1 requires training on remotely teleoperating AGV1 as well as semi-autonomous industrial robot IR1. Machines IN1 and IN2 are to be replaced with IN4 and IN5 that are WIFI networked CNC injection molding machines, meaning as a consequence that employees E2 and E3 will require training on teleoperating, monitoring, and maintaining these machines. Similarly, employee E4 is to be trained in teleoperating semi-autonomous robot IR2 that will load parts onto the conveyor for transportation to the assembly department. To enable employees to remotely handle the disruptions, ABC Ltd needs to train employees E5 and E6 on how to teleoperate the assembly robot IR3 by which the toy parts will be assembled together. This 'to-be' new scenario will make it possible for the complete operations to be handled remotely to offset the possible disruption caused by an LNG leak. However, it will have an impact on the cost investment and training required of the respective employees in the different Industry 4.0 enablers identified, i.e. semi-autonomous AGV, industrial robots (IR1, IR2, IR3) as well as smart and connected machines (IN3 and IN4). Thus, as seen, the HEI4.0 does not only help identify enablers that improve ABC Ltd's 'flow-cognitive profile' but also helps establish the related type of training required via Frame 3's matrix library including methods. Taking this approach when carrying out the initial production planning and investment, if the company considers the risk of this disaster to be high, the company could immediately cater for and plan for the possibility to automate. This would include planning of training, services, and infrastructure required for these machines to operate, and hence would make it far easier for these changes to be implemented if required.

4.3.2 *Evaluation outcome*

Based on case study demonstrations provided of how the HEI4.0 can be used and the type of guidance provided, evaluators were asked to provide feedback on the prescribed framework and also on the prototype implementation. Table 7 summarizes the key feedback obtained. As indicated, there were both positive and weak aspects associated with different frames making up the framework. Whilst that most weaknesses are attributed to how the frames and thus the prototype have been implemented, key weaknesses identified are mainly related to Frame 4.

Table 7. Strengths & weaknesses of HEI 4.0

Aspects	Strengths	Weaknesses
Frame 0	Simple and straight forward way to prioritize and highlight event risk	Timeline best defined in say weeks (e.g. in 1 week, in 6 weeks) rather than possible, first phase etc.
Frame 1	Good that it allows the characteristics of a number of activities across marketing, product design and production to be defined	Terms like 'mainly cognitive' are best quantified e.g. activity > 80% cognitive; Would be good to see the resultant 'Flow-Cognitive' profile chart;
Frame 2	Good that it provides a snapshot of possible impacts on marketing, product design and production	Not clear why impacts on prototype design are provided when say the product has been in production for two years.
Frame 3	Very good to provide users with a library of possible Industry 4.0 enablers	The framework provides a list of the most appropriate Industry 4.0 enablers. A detailed analysis of the individual use case is necessary to identify the need of other useful enablers (e.g. computer vision, AI)
Frame 4	Very useful that it provides an overview of necessary enablers and training strategies	The relative period/time required to implement the recommended enablers and training strategy should be indicated too. How would Frame 4 know if employee X truly requires certain training without having a model (database?) of the employee's CV/training?
Prototype	Using a spreadsheet is sufficient for demonstration purposes to understand HEI4.0 concept	Needs considerable improvement for use in practice. Tool should be probably implemented as a smart (AI) based system and provided as a plugin to either a CAx system or a digital twin platform.

One weakness and thus recommendation are that as part of the Frame 4 strategy, the implementation period/ time required should be indicated as this would help in taking timely corrective action. Another recommendation is that data on employees should be digitally modeled (e.g. in form of a digital qualification matrix) too so that the exact training required for Industry 4.0 enablers being introduced can be better identified. For instance, it may be the case that employee E4 already has past experience in operating industrial robots in previous employment, so in this case, he/she is already acquainted with this enabler.

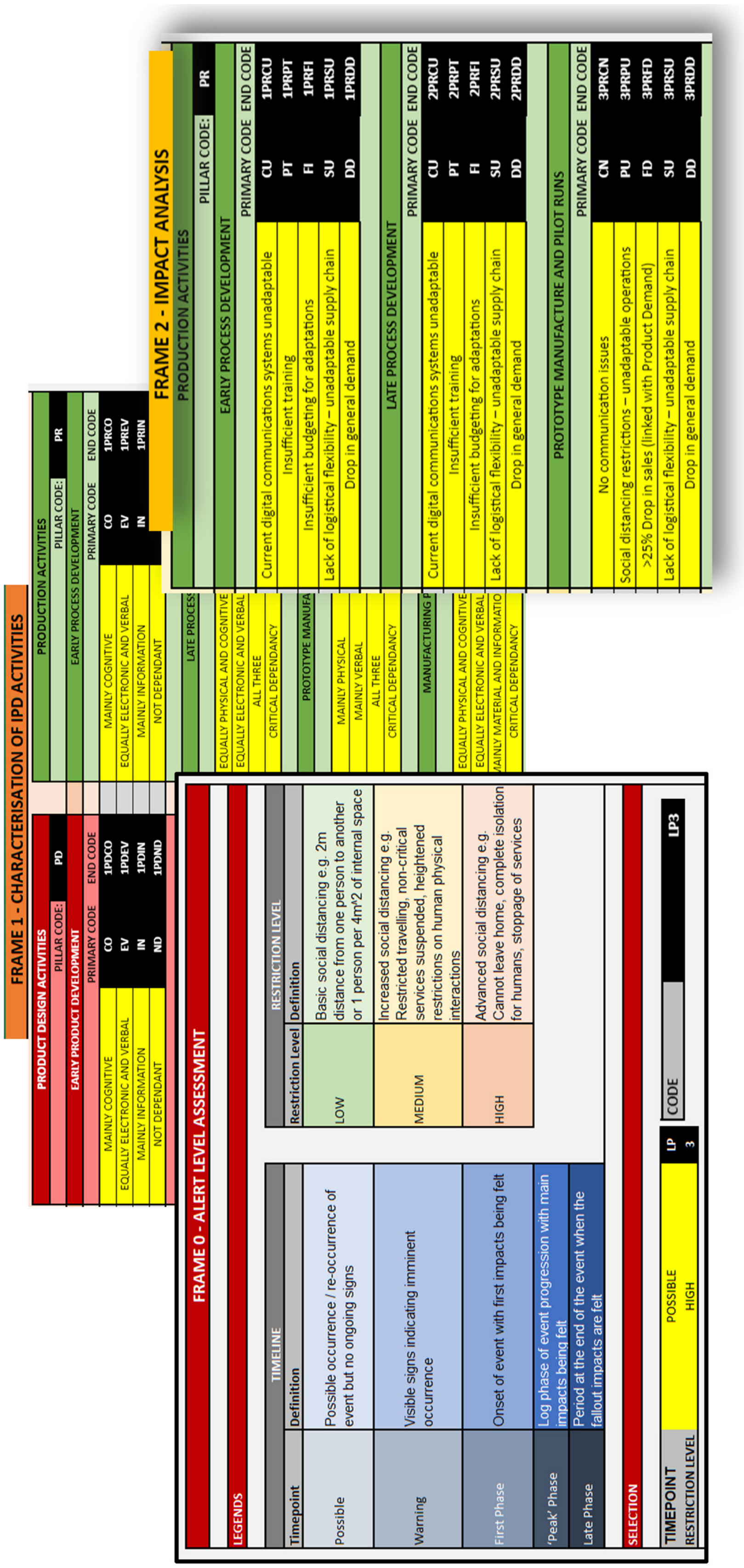
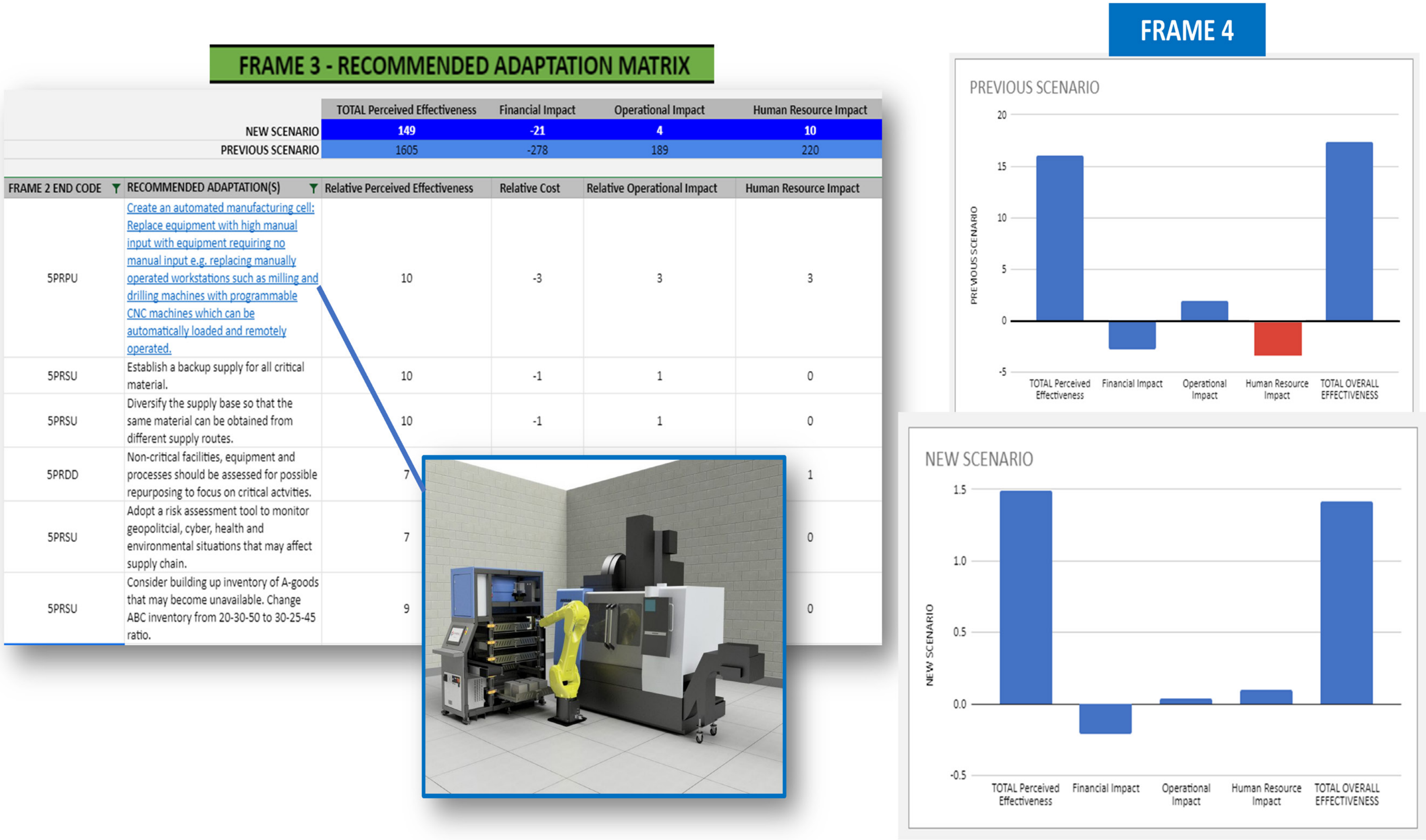


Figure 11. Frame 0, 1 & 2 case study data input and output



	TOTAL Perceived Effectiveness	Financial Impact	Operational Impact	Human Resource Impact
NEW SCENARIO	149	-21	4	10
PREVIOUS SCENARIO	1605	-278	189	220

FRAME 2 END CODE	RECOMMENDED ADAPTATION(S)	Relative Perceived Effectiveness	Relative Cost	Relative Operational Impact	Human Resource Impact
5PRPU	Create an automated manufacturing cell: Replace equipment with high manual input with equipment requiring no manual input e.g. replacing manually operated workstations such as milling and drilling machines with programmable CNC machines which can be automatically loaded and remotely operated.	10	-3	3	3
5PRSU	Establish a backup supply for all critical material.	10	-1	1	0
5PRSU	Diversify the supply base so that the same material can be obtained from different supply routes.	10	-1	1	0
5PRDD	Non-critical facilities, equipment and processes should be assessed for possible repurposing to focus on critical actvities.	7			1
5PRSU	Adopt a risk assessment tool to monitor geopolitcial, cyber, health and environmental situations that may affect supply chain.	7			0
5PRSU	Consider building up inventory of A-goods that may become unavailable. Change ABC inventory from 20-30-50 to 30-25-45 ratio.	9			0

Figure 12. Frame 3 & 4 case study output examples

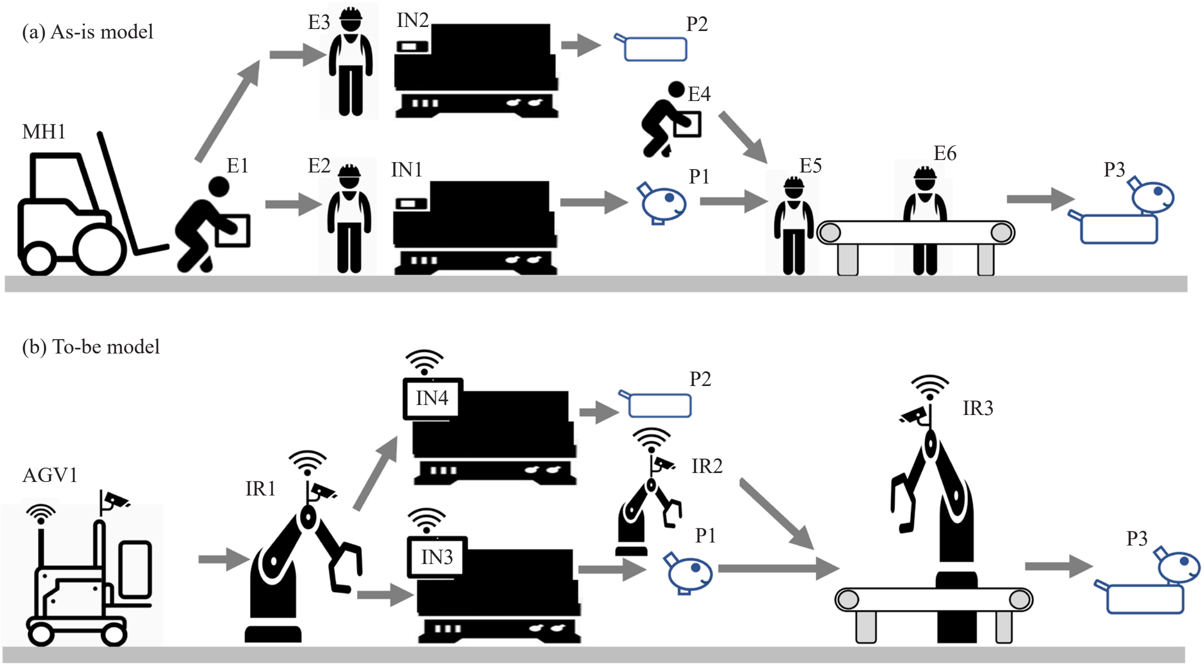


Figure 13. ABC Ltd, before and after process models

5. Conclusions and recommendations

Different manufacturing organizations have different operating architectures on which their information and material flows are based. To cope with 'COVID-like' disruptions which one can see manifested in the future for different reasons requires a manufacturing organization to be designed in such a way to make its material and information flows more resilient and thus less dependent on the physical presence of employees. At the same time, the concept of JIT on which many manufacturing organizations are based makes digital manufacturing challenging in 'COVID-like' disruptions. Our research establishes that simply introducing digital manufacturing enablers on their own is not sufficient. Rather, different organizations require that they adapt a company-specific strategy allowing them to remotely operate their manufacturing operations in COVID-19 type disruptions. In this respect, a key result emerging from our research is the concept of 'Flow-Cognitive Profile Chart' through which organizations can determine the sensitivity of their specific information and material flow architectures with respect to unforeseen scenarios such as SD restrictions. This profile chart has the concept been instrumental in the generation of our prescribed HEI Industry 4.0 Training Framework, with sub-frames 0, 1, 2, and 3 collectively termed the 'Design For Remote Assistance (DFRA)' framework aimed at re-designing the product development processes to make them more resilient by being able to be operated remotely. On the other hand, final Frame 4 comprises an Implementation Strategy responsible for realizing the solution designed, this catering also for employee training.

Experimentation performed with a prototype implementation of the HEI4.0 indicates that it contributes a step forward towards establishing company-specific strategies that prepare them for remote digital manufacturing. The HEI4.0 framework helps organizations to rapidly explore alternative Industry 4.0 enablers that make them more resilient to possible disruptions whilst simultaneously identifying the required training for different employees. At the same, the prototype implementation highlighted some improvements required to the framework and which thus merit further research including how to model and represent employee profile data so that the exact training required can be better identified. In addition, further research is required to establish guidelines on how 'Flow-Cognitive Profile Charts' can be calibrated and exploited within cyber-physical systems, based on further testing and refinements.

A long term impact of the 'Flow-Cognitive Profile Charts' concept established through our research work is that these can be exploited in digital twin models to help organizations identify and introduce relevant Industry 4.0 enablers that will shift their product development capability from one that is in the critical zone to a relatively safer zone beneath the diagonal. Embedding the prescribed HEI4.0 within a digital twin modeling approach will thus further enhance the capability of manufacturing organizations to identify Industry 4.0 enablers that will make them more resilient to SD and supply chain disruptions, whilst also establishing the relevant training required for the timely implementation and exploitation of the identified enablers.

Acknowledgements

The work reported in this paper has been supported by Erasmus+ Grant No. 2019-1-MT01-KA203-051265 funded by the European Commission called 'ICARUS – An Innovative Higher Education Institution Training Toolbox to EffeCtively AddRess the EUropean InduStry 4.0 Skills Gap and Mismatches'.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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