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Title page for Master's Thesis

Faculty of Science and Technology

Digital twin technology: A study of differences from simulation modeling and applicability in improving risk analysis.

Oula Ibrahim

Stavanger, June 2019

To Najah, Ibrahim
Tarek and Joud

Abstract

Digitalization, automation, machine learning, smart homes, AI (Artificial Intelligence), VR (Virtual Reality), smart cities and so many other terms are becoming part of almost every day's activity and can be seen integrated in all industries, driving the development of societies.

One of the latest terms which has been added to this field is "Digital Twin" which is acquiring widespread favor much more recently as digital infrastructure becomes ever more embedded in all industries, major cities and communities.

A digital twin is a mirror for a physical product, project, process or similar. It can be used to run simulations, which leading the digital twin to be considered the new generation of simulation modeling.

In this context, it is crucial to have a closer insight on this technology. It is also important to find out from a risk analysis perspective, the main differences between digital twin as a new concept and simulation modeling which has been used for risk analysis for decades. Digital twin excels simulation with many new features which would help a lot enhancing risk analysis through the lifecycle of a project, such as managing operational risk in the operation phase or supporting decision-making by providing experience data for future analysis. A digital twin could also have an essential role in the design phase by helping with alternative comparisons. in the construction phase, it would provide a great support by avoiding adverse consequences in addition to save both time and cost.

With the rapid development in technology, it is necessary to get the advantage of those new technologies to enhance risk management which achieved, in recent years, significant success by showing an important role among all different domains and industries, as well as by embracing new technologies.
The digital twin is still in its infancy stage; it requires more research to be commenced in order to enhance its use in the areas of risk management in general and risk analysis in particular.

Acknowledgment

This Master thesis is written as the final part of the MSc in Risk Management with a specialization in Risk Management at the Faculty of Science and Technology, University of Stavanger, Norway.

The inspiration to work on the thesis with this topic came up regards to all discussions among several groups including friends with several industrial backgrounds and collogues at the university, where digitalization, automation and optimization represent an essential part of all future innovations. It was a big challenge for me to take this topic since neither my background nor the information I had about digitalization and technology in general would help me through this research. It seemed as a big challenge, but I am a marathon runner and I always look for challenges. Actually, I have to admit that although with all the challenges and obstacles I faced during the research period, I enjoyed it very much, and every time a Chapter was done I was so proud, happy and motivated to continue and finish it the best way I could. To work on this topic I got the chance to cooperate with Atea AS, especially with developing the study-cases, which I am so grateful to. Working with Atea AS was a complete different experience to me which made me happy. After all I had to learn from A to Z and I would still look forward into getting more opportunities to learn more with new adventures.

First and foremost; I would like to thank my supervisor at the University of Stavanger, Roger Flage; for the amazing guidance. For the frequent meetings including all the constructive discussions. The willingness for sharing knowledge and experience. The fast and precise answers to my questions every time I need it. The inspiration when I had a complete lack of it. It has been an excellent support, thank you.

I would also like to thank every person helped me from Atea AS team; for all the meetings and their willingness to sharing their knowledge and experience with me, for spending time preparing and providing data, in addition to helping me with developing the study-cases, thank you.

All family and friends thank you very much for always being there for me showing all the support and love at my weakness moments.

My parents without those kind words and support it would not have been possible to achieve any milestone in my thesis or in my life.

My sisters, thank you very much for standing by my side every time, listening to me, motivating, supporting and encouraging me.

Last but not least, the biggest thank you is to my little family. First, to my best friend, my husband; for everything; the love, the patience, the great help, the consistent support, and for always showing confidence in me when I needed it the most. Second, to my son, for always charging me with great power, and positive energy without the intendency and without knowing how much this helped me to get the strength to continue and finish.

Oula Ibrahim

University of Stavanger, Norway, June 2019

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List of abbreviations

The following abbreviations will be used through the text:

AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
DM	Digital Model
DS	Digital Shadow
DT	Digital Twin
E.g.	For example
ERM	Enterprise Risk Management
HWE	Healthy Workplace Environment
IAQ	Indoor Air Quality
I.e.	in other words
IEQ	Indoor Environmental Quality
IoT	Internet of Things
KETs	Key Enabling Technologies
KPI	Key Performance Indicator
MBSE	Model-Based Systems Engineering
MC	Monte Carlo simulation
MCMC	Markov Chain Monte Carlo
MR	Mixed Reality
PLM	Product Lifecycle management
PRA	Probabilistic Risk Assessment
QRA	Quantitative Risk Analysis
QRM	Quantitative Risk Management
RA	Risk Analysis
R&D	Research and Development
ROI	Return on Investment
SM	Simulation Modeling
VR	Virtual Reality
VF	Virtual Factories

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1. Introduction

1.1. Motivation

New concepts with new technologies are recently in rapid development, which makes it challenging to follow up, but it is very imperative to do so and to always try to find the link between the interest of specialization with all these new technologies. In this fast rhythm, it is very important to bring these technologies to the right area and employ them in the most beneficial way.

Industry 4.0 is the new industrial revolution. It includes a broad combination of digital and physical technologies including artificial intelligence (AI), Internet of Things (IoT), cloud computing, additive manufacturing and so forth. As it has been described in (Ustundag & Cevikcan, 2018, p. 5); an essential purpose of industrial transformation is the ability to increase the efficiency and productivity of resources, consequently increasing companies' competitive power.
One of the main concepts associating with the Industry 4.0 wave is the Digital Twin (DT), which has been nominated for the last couple of years as per (Cearley & Burke, 2018, p. 17; Panetta, 2017, p. 17) as the trend No. 4 on top 10 strategic technology trends.

The Norwegian Directorate of Public Construction and Property (Statsbygg) recently stated that any new construction project, managed by them, should be accompanied by developing its digital twin. This statement could become the start of a new age of construction regulations in Norway and therefore in Europe or even worldwide (Hagen, 2018).

The concept of risk has become one of the most important fields of study in all sectors including finance, Industry and so on. For that, simulation modelling has been used for decades when performing risk analyses and risk assessments.
As DT has been more and more recognized as a strategic tool adding a significant value when being deployed, in addition to being on its way to become part of the regulations in Norway. It has become essential therefore to start defining the differences between this technology and simulation modeling in order to elaborate and clarify both concepts clearly, as well as to find the way of employing this technology when carrying out a risk analysis.

All that has been mentioned above motivate further studies and academic research on these topics. Hence, this thesis has been chosen in this domain; it includes reviewing scientific literature, performing comparisons, presenting and developing study-cases, as well as discussing and summarizing what has been understood by the end of this study.

1.2. Objectives

This thesis has two main objectives:

1. To discuss from a risk analysis perspective, how the digital twin concept is different from simulation modeling, which has been used for risk analysis for decades; and to discuss, conceptually, how this new technology can be used to carry out an improved risk analysis.
2. To develop study-cases using a specific digital twin to clarify the applicability of digital twin in support of risk analysis or parts thereof, from different phases of the life cycle of a project.

In order to meet these objectives, the following will be done:

- Present a scientific literature and theory review, including comprehensive information on risk analysis, simulation modeling as well as introducing the most used methods from simulation modeling for risk analysis.
- Introduce a detailed explanation of the digital trends and digital twin technology.
- Illustrate the link between the two concepts; digital twin and simulation modeling, and then perform a comparison, first from a general perspective and afterward from a risk analysis perspective.
- Present an example of a simplified risk study to an office building DT, including opportunities and threats among different phases of its lifecycle. Also, three study-cases will be developed from different cases and applications of the same DT in order to help reducing risk in different phases of a project lifetime.
- Highlight main positive points about employing digital twin when carrying out risk analysis, as well as showing some challenges and limitations of this technology.

1.3. Scope and delimitations

The scope of this thesis, as described above, is to highlight with a brief explanation the differences between digital twin and simulation modeling by performing a comparison and then to define the relevant applications and benefits of the new characteristics of digital twin to enhance risk analysis, in any phase of the lifecycle of a project, system or similar. Although the thesis is putting some focus on simulation modeling in literature at the beginning of the dissertation, the main focus will be on digital twin which is the new concept on the top of interest among all industries. As the specialization of studies of this dissertation is in Risk Management, discussions and results obtained are limited only to the risk analysis perspective.

The comparison between the digital twin and simulation modeling is primarily going to be literature-based, but it will as well include conclusions and points based on brainstorming and logical inference.

The study-cases will be developed in cooperation with Atea AS. Where all the needed data in addition to the explanations about how does the system engine work are based on sharing knowledge and experience of people working in the industry and having good practical experience in this field. Whereas, taking the part of cases in addition to discussion linking it to risk and taking it from a risk analysis perspective are literature-based.

Discussions, comparisons, consequences evaluation, in addition to highlighting limitations and challenges of digital twin technology are all conclusions after reviewing all the used resources in addition to the knowledge and experience gained through the whole period of this study.

1.4. Structure of thesis:

The remainder of the paper is structured as follows:

Chapter 2, which is mainly to outline the chosen methods for this dissertation, besides including a table showing the main search engines and keywords that were utilized in order to find the literature.
Chapter 3 would include scientific literature and theory review for the simulation modeling methods, and to explain further in more details about the most used simulation modeling methods when performing a risk analysis.
Chapter 4 will include an explanation about the digital trends and the digital twin technology.
Chapter 5, will outline the link between digital twin and simulation modeling in addition to perform a comparison between the two technologies from risk analysis perspective and usage in.
Chapter 6 will continue by presenting a simplified risk study to an existing office building DT, including highlighting the opportunities and threats of different phases of its lifecycle in.
Chapter 7 will continue by developing study-cases using the same digital twin from Chapter 6 and having some provident of what has been discussed before to support the theoretical discussions and explanations afterward.
Chapter 8 which includes discussion and reflection on all the information from the former chapters.
Finally, Chapter 9 is a conclusion.

2. Research Methodology

Since digital twin is considered relatively a new technology, the information found, displayed and analyzed in this thesis could be in fact, sometimes, inconsistent or not standardized due to the lack of resources and references thus the related literature is still minimal. The same applies when digital twin is utilized for risk analysis as it is still challenging to find resources discussing this topic as well as comparing digital twin to simulation modeling.

This thesis aims to analyze the current available sources in order to create a broader picture which could be the solid basis for a complete future research by utilizing the obtained information as well as formulating a discussion leads to a conclusion.

The theoretical basis in Chapter 3 has two parts; the one about risk is mainly based on the literature as a part of the curriculum for MSc in Risk Management at the University of Stavanger, Norway. Whereas, the one about simulation, is based on articles, books, and similar related researches and studies that give an excellent theoretical basis for the plotted points.

Chapter 4, related to digital trends and digital twin technology which is primarily built on articles, scientific journals and similar findings due to the fact that digital twin is a nascent technology. Therefore, the literature available is still limited to researches and articles with limited availability of books.

Inferences drawn in Chapter 5 and following in Chapters 6 and 7 are based on the basis provided in the early chapters of the thesis as well as on meetings with experienced people from Atea AS since they have some experience working on the new digital twin used for the study-cases. Where, in order to assess better the topic, some interactive tasks have been done in Chapters 6 and 7. Chapter 6, includes a study on an existed digital twin which covers the identification of initiating events (opportunities and threats) for different phases of the lifecycle of the project. In order to get this task done, structured brainstorming in which questions, as well as checklists, have been used to reach the results illustrated in that Chapter. Chapter 7 includes three study-cases on the same digital twin that were developed in addition to the following discussion. This way, a more comprehensive understanding supported by an up-close, in-depth, and detailed examination of the subject was achieved.

All literature review is used as well to find and explain the link and differences between the two studied concepts as well as its role in enhancing risk analysis.

The discussion in Chapter 8 is based on the basis provided in the first part of the thesis in addition to the information provided through the study-cases.

TABLE 1 SEARCH ENGINES AND KEYWORDS USED FOR THE LITERATURE SEARCH

Search engines:	Search - key words:
scholar.google.com	"digital twin"
	digitalization
	"Industry 4.0"
	"Simulation modeling"
	"Monte Carlo Simulation"
	"digital twin" and "risk management"
	"digital twin" and "risk analysis"
	"digital twin" vs "simulation"
	"digital twin" vs "simulation modelling"
google.com	"digital twin"
	digitalization
	"Industry 4.0"
	"simulation modelling"
	simulation
	"digital twin" vs "simulation"
	"digital twin" vs "simulation modelling"
	API
	"JAVA code"
	"Operational Risk"
	"Indoor air quality"
	"healthy workplace environment"
oria.no	"Risk assessment" And "digital twin"
	"security risk assessment"
	"Industry 4.0"
	"Simulation modelling"
	"Simulation modelling" And "Risk assessment" And "Risk management"
	"Monte Carlo Simulation"
	"digital twin" and "risk management"
	"digital twin" and "risk analysis"
	"digital twin" and "simulation"
	"digital twin" and "simulation modelling"
	"Risk analysis" and "maintenance"
	"Operational Risk"
sciencedirect.com	"Risk assessment" And "digital twin"
	"security risk assessment"
	Digitalization
	"Industry 4.0"
	"Simulation modelling"
	"Simulation modelling" And "Risk assessment" And "Risk management"
	"Monte Carlo Simulation"

	“Monte Carlo Simulation” And “Risk assessment” And “Risk management
	“digital twin”
	“digital twin” and “risk”
	“Risk analysis” and “maintenance”
scienceresearch.com	“Risk assessment” And “digital twin”
	“security risk assessment”
	“Industry 4.0”
	“Simulation modelling”
	“Simulation modelling” And “Risk assessment” And “Risk management”
	“Monte Carlo Simulation”
	Digitization
	“digital twin”
	“digital twin” and “risk”
	“digital twin” and “simulation”

Table 1 is to show some of the search engines and some of the keywords that were used in order to find the literature for the thesis.

3. Scientific Literature and Theory Review

This Chapter is about introducing some theoretical basis which is necessary for the comprehension of further chapters, first of all by defining and introducing risk, the risk concept, and risk analysis. Secondly, by defining simulation modeling, methods that have been used, with a more comprehensive explanation about the Monte Carlo Method since it is the most used method in the risk management field, then to continue with the simulation modeling for risk analysis. Third and last, a brief explanation of the Quantitative Risk Analysis (QRA).

3.1. Risk

3.1.1. The Risk Concept

Different methods are available to understand the risk concept, which is why definitions of risk concept have been presented from different perspectives. Some definitions are based on uncertainties, some on undesirable events, and others on expected values and probabilities (Aven & Renn, 2010). In addition, some experts believe that risk is the same as risk perception, e.g., (Jasanoff, 1999), but others disagree with this belief and argue that risk perception is relative to the assessor, his experience, background, situation and so forth (Aven, 2011; Aven & Renn, 2009). This difference between risk and risk perception can lead to many inconsistencies, which make it very important to be highlighted. For example, a young car driver might believe that the risk associated with driving fast in a narrow winding road has a very negligible level. Meanwhile, an experienced driving instructor would assess this specific situation as a high risk. Thus, the risk in this situation is the same, the only difference is the risk perception.

Aven and Renn (2009, p. 6) suggest understanding the risk associated with a certain activity such as:

"Risk refers to uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that humans value."

The main features of that suggested understanding are illustrated in Figure 1. The risk refers to uncertainty about events and consequences of related to the activity, taking into consideration the severity of the events and the consequences. Severity is a way of characterizing the consequences, and it refers to potential measures such as size, extension, etc. It also takes in consideration the value of loss (money, lives, environment, etc.). For example, a way of classifying the severity of the consequences is the number of fatalities.

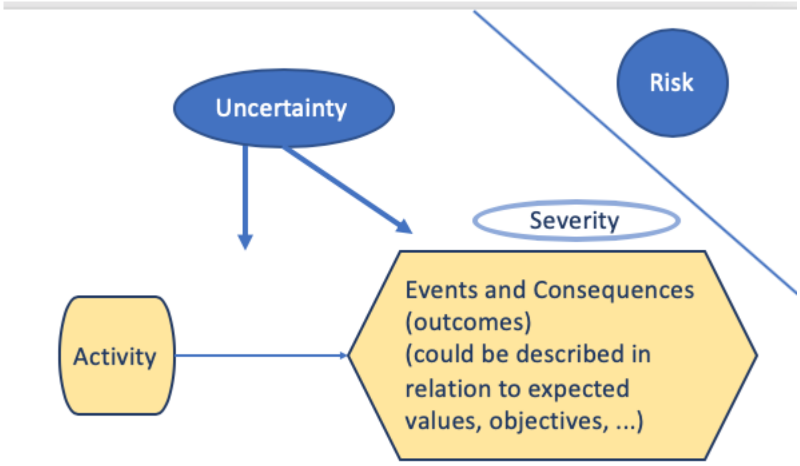


FIGURE 1 ILLUSTRATION OF THE RISK DEFINITION, ADJUSTED FROM (AVEN, 2011, P. 721; AVEN & RENN, 2009, P. 7).

Aven (2011, pp. 720, 721) describes, this understanding of risk concept which expresses that some events could occur as a result of a certain activity which leads to consequences (outcomes) that could be more or less severe. These outcomes are defined in relation to expected values, objectives or other references. As well, there are uncertainties related to the occurrence of these events and their consequences. The events could become part of the consequences of the activity, which would simplify the set-up.

3.1.2. The definitions and descriptions of risk and vulnerabilities

It is almost impossible to present all the definitions of risk used in the scientific risk fields.

Therefore, the definition which will be highlighted here is the one which can be found in (Aven, 2015); the two main dimensions for risk are consequences and uncertainties, covers that an activity leads to some consequences C that are not known-they are uncertain, which can be illustrated as (C, U) where C stands for consequences and U for uncertainties.

Furthermore, Aven (2015) points out that the best general description of risk can be written as:

Risk description = (C’, Q, K), or alternatively (A’, C’, Q, K); A’ some specified undesirable A events, and where K is the background knowledge on which Q a description/measure of uncertainty and C’ some specified consequences, are based.

The vulnerability as Aven (2015) describes, is a risk conditional on the occurrence of an event A. Therefore, it has been mentioned that the vulnerability concept is being used usually when there is a concern about the consequences, given that an event has occurred (initiating event).

Thus, the general form of the vulnerability description with reference to (Aven, 2015) is (C', Q, K | A)-using the same notation used earlier.

As Aven (2015) further explains, vulnerability is an aspect of risk, and performing a vulnerability analysis is part of the risk analysis, which is called risk and vulnerability analysis in case of highlighting vulnerability in the analysis.

3.1.3. Risk Analysis

To describe risk and furthermore to build a risk picture that would be the primary objective of a risk analysis (Aven, 2015). The main task of a risk analysis is to identify the initiating events and to build the causal and the consequences´ picture using an appropriate risk analysis method.

Aven (2015) differentiates between three main categories for the risk analysis methods which are categorized according to the degree of complexity, and to how quantitative or qualitative the method is.

Category	Simplified RA	Standard RA	Model-based RA
Type of analysis	Qualitative	Qualitative or quantitative	Primarily quantitative
Description	-Informal procedure. -Establishing a risk picture by brainstorming sessions, group discussions.	-More formalized procedure. -Using recognized risk analysis methods. -Using risk matrices to show the results.	-Using techniques to calculate risk.
Example	Presenting risk on a coarse scale.	SWIFT and HAZOP.	Fault tree and event tree.

TABLE 2 THE MAIN CATEGORIES OF RISK ANALYSIS METHODS, BASED ON (AVEN, 2015).

It is obvious from Table 2 that there are two main types of analysis, quantitative or qualitative. It is vital to differentiate between those two types. The first type is being described as difficult to use because of the appliance of very complex statistical and mathematical methods. The second type is being described as it does not produce enough information outputs because of using adjectives when analyzing risk instead of mathematics (Wawrzyniak, 2006).

A risk analysis can be performed at different phases of the lifetime of a project/system, and it has many reasons to be performed, the main one is to support decision-making. It also has many benefits; such as providing an excellent basis to find the correct balance between different concerns, e.g., between cost and safety (Aven, 2015).

Aven (2015) points out the importance of distinguishing between a project planning phase and operation phase, highlighting that the best is to perform a risk analysis in the planning phase. This is due to the flexibility that exists in this phase. Thus, it would be more comfortable, cost-efficient and more effective to compare alternatives, choose between different solutions or even to perform primary changes and modifications. At the same time, there will always be a knowledge gap that will be gradually covered, which will facilitate the possibility of utilizing a more comprehensive method. In the planning phase, the best option is to use a relatively coarse analysis method until more data are further available in the operation phase. That being mentioned does not mean that risk analyses are not highly significant in all phases, but choosing the most suitable method to fulfill all requirements and objectives is inevitable.

The three main elements of risk analysis illustrated in Figure 2 and with reference to (Aven, 2015) are:

1. The planning phase.
2. The risk assessment phase.
3. The risk treatment phase.

These three elements conclude the term “risk analysis process” which has been used in (Aven, 2015) while the term “risk management process” has been used when other management elements have been included.

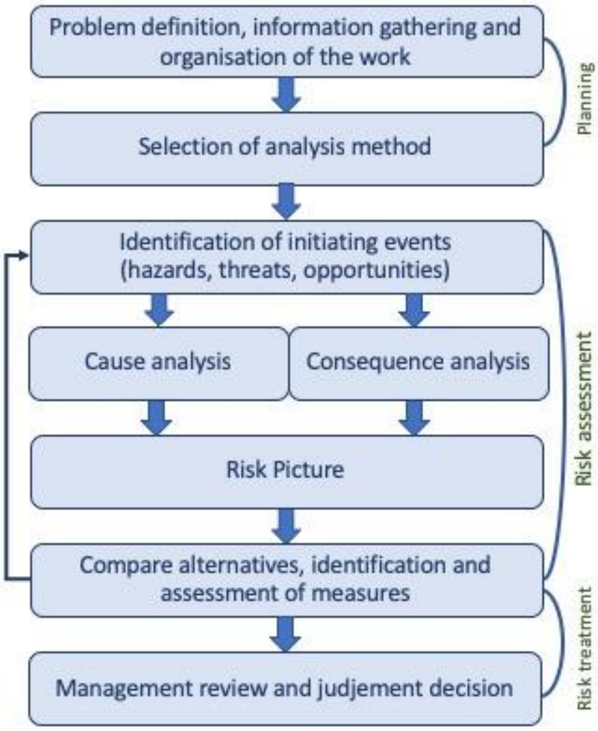


FIGURE 2 THE MAIN STEPS OF THE RISK ANALYSIS PROCESS, BASED ON (AVEN, 2015, P. 6).

Aven (2015) explicates about the three elements of risk analysis, as seen in Figure 2, as follow:

- The planning phase is about identifying the problem, working on gathering information, and selecting which analysis method is the most suitable one to work on the defined problem.

- The risk assessment phase which is considered as the core part of the analysis is first about identifying the initiating events (e.g., hazards, opportunities, threats) and second to conduct cause and consequence analysis, then finally comes the establishment of the risk picture.

- In a later stage begins the risk treatment which consists of two stages: performing a comparison including alternatives that are available according to the risk picture, then performing a process of identifying and assessing the measures to treat the risk. The last step would be the management review and judgment which is being considered as one of the most critical steps of the complete analysis, as it shows how the data provided is going to be used, followed by the final decision of how to treat the risk.

The results that come out of risk analysis are being evaluated; the term risk assessment is used to demonstrate both the analysis and the evaluation.

⇨ Risk assessment = Risk analysis + Risk evaluation (Aven, 2015, p. 5)

3.2. Simulation modelling

3.2.1. Simulation

The simulation has been defined over the last decades in different ways:

The definition found in Cambridge dictionary is "a model of a set of problems or events that can be used to teach someone how to do something, or the process of making such a model" (“Simulation,” 2019a).

The one in Wikipedia is “an approximate imitation of the operation of a process or system (Banks, 2001); the act of simulating first requires a model is developed. This model is a well-defined description of the simulated subject and represents its key characteristics, such as its behavior, functions and abstract or physical properties. The model represents the system itself, whereas the simulation represents its operation over time" (“Simulation,” 2019b).

The market definition as per (Allega & Norton, 2018, p. 2) is “Simulation and modeling software allows users to approximate complex systems in which its properties and behavior mimic the actual system of interest. Behaviors can then be studied through analytics of the simulation model to produce predicted outcomes based upon complex systems. Further insight into system behavior can be gained by animating the model to visually engage leadership teams. Artificial intelligence (AI) and machine learning (ML) algorithms may further drive suggested results of properties under behavioral conditions”.

In general terms, it is the process of designing a model of a real system and carrying out experiments with that model to have a better understanding of that system behavior and evaluate various strategies for the system operations.

In fact, it is the technique of getting information about how something is going to behave without having to test it in real life. That will lower the chances of errors and increase the ability to make the right decisions for any project when understanding whether and under which conditions this project could fail.

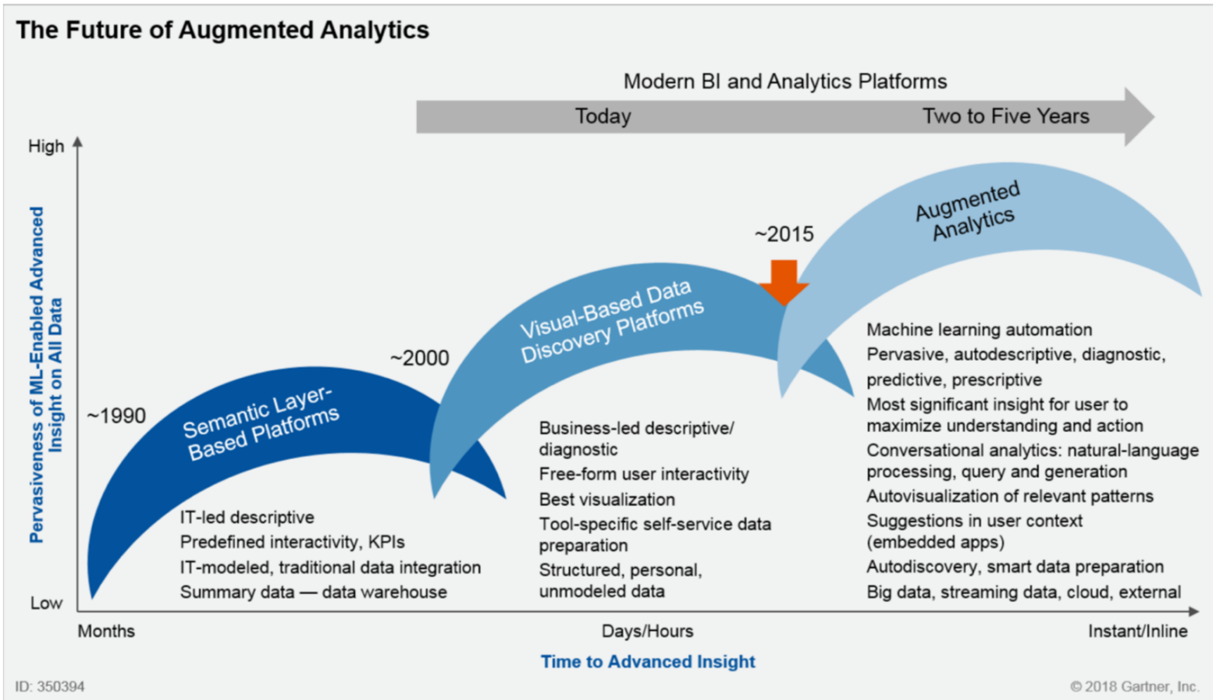


FIGURE 3 THE PROGRESSION OF AUGMENTED ANALYTICS AND THE FUTURE OF SIMULATION AND MODELING, WITH REFERENCE TO (ALLEGA & NORTON, 2018, P. 14)

Simulation tools have become crucial and essential tools for decisions-making. Combining decision support with integrated asset modeling could strengthen the overall analysis. These tools are becoming more influential in operations, specifically with business development and process optimization. Furthermore, simulations are helping with creating more value-added from the same input in addition to maximize the profits.

In other words, simulation and modeling tools' primary value would be granting the user the capacity to test different alternative scenarios and to examine the afterward impact these alternatives will have on the project. The excellent advantage of these tools would be the ability to grant users a high success rate without experimenting in real life, which is often cost-prohibitive or completely unfeasible. (Shetty, 2017)

As simulation is in continuous evolution, it always has the intention to embrace new concepts such as artificial intelligence and machine learning, as applying these concepts to simulation and modeling are still in their infancy. However, Allega and Norton (2018, p. 14) illustrate prediction on the future of augmented analytics as seen in Figure 3, where the next two to five years' expectations of this advancement could be seen.

3.2.2. Monte Carlo Simulation

The following discussion is a summary of what is understood after reading the information from (Alexander J. McNeil, 2005, pp. 52, 53; Manno, 1999, p. 9; Maria L. . Rizzo, 2008; Vose, 1996, pp. 10, 11, 12, 2008, pp. 532, 533):

Monte Carlo Simulation (MC) is a statistical method based on random sampling. This computerized mathematical technique is a perfect tool for establishing a probabilistic model of nearly any complexity. It requires a bit of probability mathematics to present the model. One of its critical disadvantages is that all the parameters should be quantitatively determined with uncertainty (when applicable) before running the model and making a projection of possible observations.

This technique is one of the key tools or i.e. it is a general name for any approach to risk measurement that includes the simulation of a specific parametric model for risk-factor changes. In this type of application, the method could be either conditional or unconditional, this depends on the adopted model, whether it is a dynamic time series model for risk factor changes or a static distribution model.

Oftentimes, the risk assessor can use MC as a tool into constructing risk assessment models, using several products like Analytica, Simul8, @RISK, Crystal Ball, and bespoke Visual Basic applications, among others.

Historically, as Rizzo in (2008, p. 119) and Manno in (1999, p. 9) explain, the Monte Carlo method was developed after World War II in the late 1940s. It was first used by scientists working on the developing the atomic bomb. However, the idea of random sampling was not new at that time, e.g. in 1777, Comte de Buffon used a random experiment to empirically check his probability calculation for "the famous Buffon´s needle experiment".

J. von Neumann and S. Ulam are considered as the creators of the MC method. As described above, random numbers have an essential role in this method. Monte-Carlo renowned for its casinos, and the roulette of course can be basically described as a random number generator (A random number generator (RNG) can be described as a computational or physical device which is designed in sake of generating a sequence of numbers which seem to be independent draws from a population, which pass a series of statistical tests as well (Law & Kelton, 1991; Raychaudhuri, 2008)). This explains why this method was named for Monte Carlo. Since its introduction in World War II, Monte Carlo simulation has been used to model a variety of physical and conceptual systems. On the contrary, Vose in (1996, pp. 40, 41) notes that MC got its name during World War II from the code name of an American project on the atomic bomb, but not from the town in Monaco with the same name that is well known for its casinos, as many people believe. This contradiction and disagreement on the method name story emphasize the importance of this method.

How does Monte Carlo simulation work?

As Vose describes in (1996, pp. 10, 11, 2008, pp. 16, 17); MC involves the random sampling of each probability distribution within the model to generate hundreds or maybe thousands of iterations (it can also be called scenarios or trials). Each probability distribution is sampled in a manner that regenerates the distribution's shape. Noting that, the probability of the values that might occur has been reflected by the distribution of the values which have been calculated for the model outcome.

Advantages, disadvantages and weaknesses of Monte Carlo simulation:

MC is a widely accepted simulation technique and simple to apply, it offers many advantages over other available simulation techniques, but like any other method, it has some disadvantages and weaknesses point at the same time.

Advantages:

- MC is conceptually a simple and easy to use method in order to reach the likely outcome in case of an uncertain event and an accompanying confidence limit for the outcome. It can be employed in developing random sequences of scenarios that suit preset characteristics from a collection of different scenarios. This useful technique facilitates the process of making a decision for the decision-maker based on numerical data. Moreover, it is a helpful technique for scheduling and cost analyzing, therefore, by using the Monte Carlo analysis, it is possible to add the cost and schedule risk event to the forecasting model with a very high level of confidence. Additionally, MC analysis can be used to find the likelihood of meeting the project milestones and goals.
- Whereas in his book, Modarres (2006, pp. 232, 233) enumerates the following advantages of MC:
    - An extensive sampling from the input elements' ranges. Thus, this extensive sampling from the individual variables permits for the identification of nonlinearities, discontinuities, and thresholds.
    - Unlike many other methods, it is possible in MC to use the model directly without any need to depend on surrogate models, e.g., the need to use Taylor series expansion or response surface which demand additional simplifying assumptions.
    - This method does not require extensive modifications and manipulation of the original model.

- Furthermore, from his point of view, in his books (1996, pp. 10, 11, 12, 2008, pp. 16, 17, 18), Vose highlights and lists the advantages that MC offers as follows:

    - It is possible to model the correlation and other inter-dependencies.

- Performing an MC does not require a vast deep understanding of complex mathematical equations.
- All the necessary work for determining the outcome distribution can be done by the computer.
- Automation software involves in simulation can be easily found.
- It is possible to include complex mathematics without any additional difficulties.
- Since MC is vastly known as a reliable and powerful technique, its results are more likely to be accepted.
- Investigating model behavior can be simply done.
- The model can be changed easily, and a comparison of the results with prior models can be made quickly.

Disadvantages and weaknesses:

- In (2006, pp. 232, 233), Modarres explains that a disadvantage of MC is the computational cost which appears in two cases: first in case of dealing with complex forms, and second in case of dealing with probabilities that are very close to either zero or one.
- In (2008, pp. 17, 18, 209–212), Vose explains that MC is oftentimes criticized as being an approximate technique, but Vose further explains that achieving a higher level of precision can be easily done by increasing the number of trials in the simulation. Thus, the limitations are in the number of random numbers that can be produced from a random number generating algorithm, in addition to the time the computer takes to generate the trials. These limitations can be irrelevant for any of the existed problems, or it is possible to avoid them by splitting the model into convenient sections where the end of each section becomes the starting point of the next section. What is important in such cases is to split the model in a way that the end of a section is providing enough trials of interest for us to be sure of the parameter value or distribution at that point.
- Alexander (2005, pp. 52, 53) explains that a weak point of MC method is that it cannot solve the problem of finding a multivariate model and the achieved results will just have the same level of the model which has been used (results are as good as the model).

STEPS OF MONTE CARLO SIMULATION:

As per (Raychaudhuri, 2008), the following steps are typically performed for the Monte Carlo simulation:

- Identifying a statistical distribution which will be used as the source for each of the input parameters.

  (Statistical distributions or, i.e., probability distributions characterize varying a random variable outcome, and the probability of occurrence of those outcomes. In cases, as the random variable takes only discrete values, the corresponding probability distributions are called then discrete probability distributions, e.g., the binomial distribution, Poisson distribution, and hypergeometric distribution. In other cases, as the random variable takes continuous values, the corresponding probability distributions are called then continuous probability distributions, e.g., normal, exponential, and gamma distributions (Raychaudhuri, 2008).)

- Drawing random samples from each distribution, which will represent the values of the input variables.

  (Random sampling: this term has been identified in (Raychaudhuri, 2008, p. 92) as follows: "In statistics, a finite subset of individuals from a population is called a sample. In random sampling, the samples are drawn at random from the population, which implies that each unit of population has an equal chance of being included in the sample.")

- Each set of input parameters produces a set of output parameters, and each output parameter has a value of one particular outcome scenario in the simulation run.
- Collecting the output values from a number of simulation runs.
- Perform statistical analysis on the obtained values of the output parameters.
- Using the performed analysis to help to make decisions about the course of action.
- It is important to note that it is possible to use the output parameters sampling statistics into characterizing the output variation.

3.2.3. Markov chain Monte Carlo model

Markov Chain Monte Carlo (MCMC) models considered as a superior method to MC, constructing an MCMC model is likewise to constructing an MC model, but it has some extra advantages. One is the advantage of the possibility of incorporating any available data at a stochastic node of the model into the model. Therefore, the model produces a Bayesian revision of the system parameter estimates. Models of possible interventions can be run in parallel that then estimate the effect of these changes. Another and more important advantage of this model is that all available information can be incorporated in a statistically consistent fashion. WinBUGS is a great software that can be used when implementing an MCMC approach, but it is pretty difficult to use; in addition to that, the required computational intensity for MCMC modeling means that it is not possible to use models of the level of complexity that is currently standard (Vose, 2008).

3.2.4. Simulation modelling for risk analysis

In his book (2008, p. 63,64) Vose highlights two essential and useful rules for risk analysis modeling.

The first one which has been referred to as "the cardinal rule" is: "Every iteration of a risk analysis model must be a scenario that could physically occur", Vose explains further that if the modeler follows this rule, a better model would be produced, which would be more accurate and realistic.

The second one is: "Simulate when you can´t calculate," which degrade the need for simulation when typical mathematical calculations are applicable. However, Vose further elucidates that a concluded result of a simulation is approximate where mathematics can provide an exact one. Besides, there is a high chance that simulation does not provide the entire distribution, especially at low probability tails. In most cases, it is easy to update the mathematical equations in case of any variation in the value of a parameter. Although, the possibility of using some techniques like partial differentiation to mathematical equations provide more methods to optimize decisions which can be performed with less effort than performing a simulation. With all the highlighted benefits there is still the fact that algebraic solutions are time-consuming and require high mathematical skills apart from simulation that is usually easier to perform, does not require high mathematical skills, and a good and intuitive approach to modeling risky issues.

3.3. Quantitative Risk Analysis

There are two essential key features for most problems in the life cycle of a project. Those two features are risk and uncertainty. It is imperative to understand them in order to come up with the best logical decisions (Vose, 1996, p. 1). As Modarres illuminates in his book (2006, p. 6) Quantitative Risk Analysis (QRA) aims to estimate the risk in form of probability of a loss (several techniques have been devised to calculate the outcome distribution) and evaluate these probabilities in order to come up with decisions, perform checks, communicate the results. Sharing these results is usually the first step for precise identification of a problem with the intention to start finding and discussing and allocate possible solutions. Though, the uncertainty which is associating the estimation of the probability of having undesirable events with undesirable consequences, e.g. losses, are characterized by using the probability concepts (Figure 4 bellow, with reference to (Vose, 1996, p. 8), illustrates some examples of different distributions that are very common to be used; where the horizontal axis (x-axis) covers the range of possible values that the variable could take and, the vertical axis (y-axis) gives each value within that range a probability weighting). However, uncertainties associated with the quantitative results have a crucial impact on how to use the results in case of not available data and evidence.

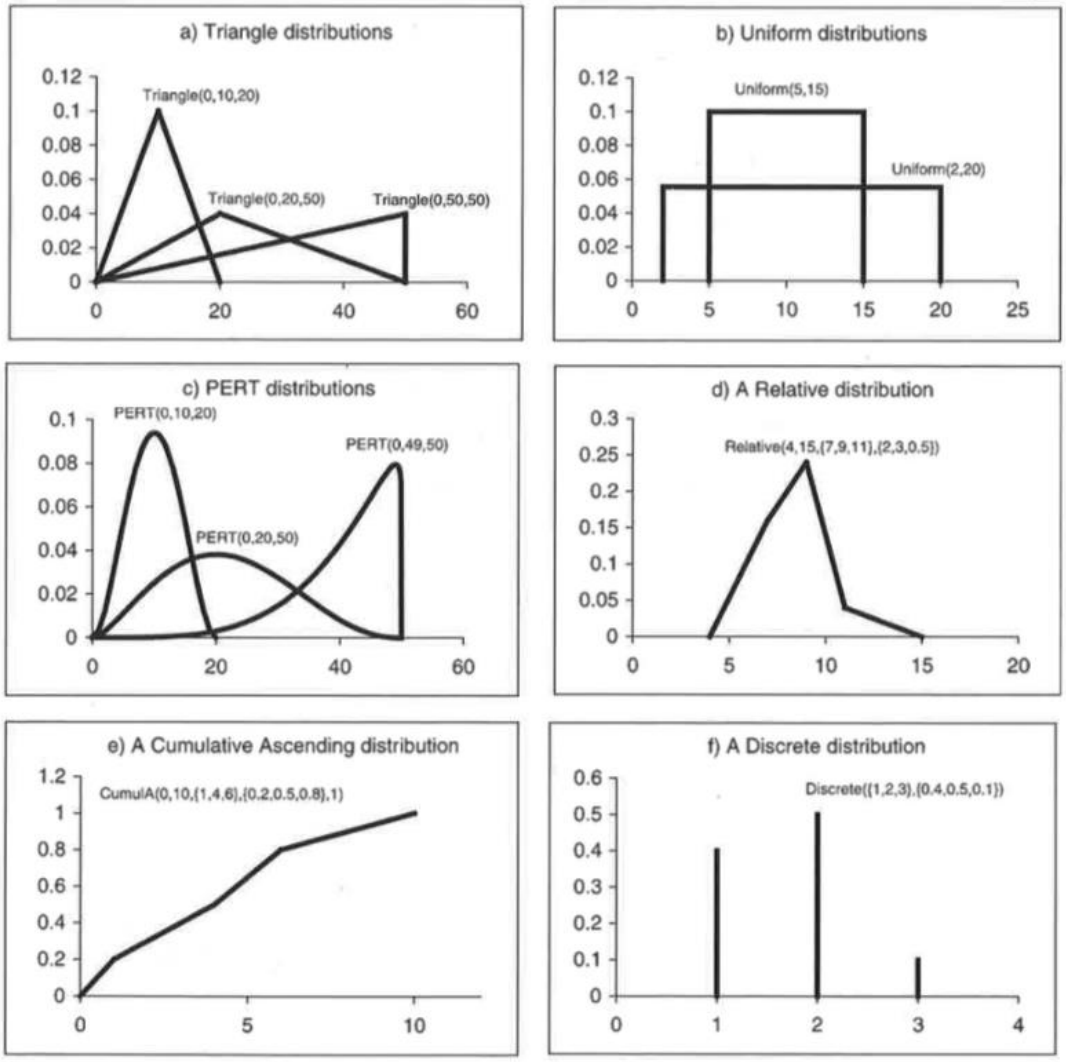


FIGURE 4 EXAMPLES OF PROBABILITY DISTRIBUTIONS WITH REFERENCE TO (VOSE, 2008, P. 46)

Quantitative risk analysis with simulation modeling has been increasingly used for decades. Monte Carlo Simulation, is the most used simulation technique in the risk management field since it offers the user a powerful and precise method regarding understanding the different uncertainties of a problem and producing a logical estimation of the problem´s total uncertainty (Vose, 1996, p. 1,8,9). As described earlier in Section 3.2.2 and in quantitative analysis, MC aids the decision-maker and facilitates the decision-making. It builds models of possible outcomes and substitutes a range of values a probability distribution for any factor that has inherent uncertainty. Then it would calculate the outcomes several times, using every time a new set of random values out of the probability functions, thus helping to make informed project decisions.

3.3.1. Common simulation modeling methods in risk analysis

Several techniques, models and methods that exists can be used as a tool to give insight when carrying out a risk analysis; the most used one is the Monte Carlo simulation.

As explained in (Allega & Norton, 2018, p. 7); Simulation may be carried out in two ways:

- Deterministic simulation represents input parameters using single values. The used single value could be varied with what it represents depending on a case study; e.g., an average, the best estimate, a best-case scenario or maybe a worst-case scenario, etc. This type of simulation can be appropriate for particular problems; e.g., simulating the performance of a machine. Deterministic simulations sometimes do not succeed in capturing the variability or the complexity of inputs and constraints in the supply chain.

- Stochastic simulation is the process of modeling a variable business ecosystem and analyzing the present or future status of that ecosystem. Where probability distributions of the possible values of different inputs are being used to express variability.

It is further explained in (Allega & Norton, 2018, p. 7) that; besides the variability issue, simulation models follow one of four different approaches of modeling, those approaches are:

- Discrete Event Business Process Simulation: This approach approximates the system or the process performance as a sequence of discrete events. For example, simulating factory performance in a manufacturing environment with discrete events, ranging from a machine shutdown or the arrival of inbound inventory.

- Agent-Based Simulation: This approach is considered as a specialized kind of discrete event business process simulation that is decentralized and focused on individual entities or agents which could be for example companies, people, machines or even projects. Noting that the overall performance of the global environment is determined based on two things, the first one is the behavior of each agent and the second one is how they interact together. For example, in supply chain, agent-based simulation can model an ecosystem of trading partners. The determination of the global performance of the ecosystem is based on; first, how each partner operates and second how each partner's behavior affects the behavior of other partners.

- System-of-Systems Simulation: This approach has been defined in academic literature in many ways. There is an agreement between most definitions that this approach allows these three; the multiple, heterogeneous and distributed systems to be considered within an ecosystem of agents plus their discrete-event business processes behaviors. Nevertheless, this type of simulations does not usually consider all details of the individual properties, for example, a single person in a discrete event business process. Instead, it aggregates a representation of people, services, products and processes within an economic market consisting of other aggregate suppliers, partners, regulators, etc.

- Continuous Simulation: This approach is better to be used when it is possible to describe the entity or a system being simulated as it moves continuously over time, rather than in discrete steps. E.g., the most suitable way to represent the simulation of fuel movement in a pipeline is by using a continuous simulation. In the continuous simulation, simultaneous change of current and target state environments is considered instead of comparisons in the state that are static.

Many specific models have been developed based on industrial demands and for the purpose of utilizing these models. For example, ecosystems (Rickebusch et al., 2008), agricultural crops (Naylor, Battisti, Vimont, Falcon, & Burke, 2007), tourism (Lise & Tol, 2002), and insurance (Changnon & Changnon, 1998).

A disadvantage of this integrated approach is that it requires ample computing and data resources, which limits the development of mitigation and stabilization scenarios. Adhering to a comprehensive set of assumptions throughout the causal chain and expressing impacts as risks also remains difficult (Jacxsens et al., 2010).

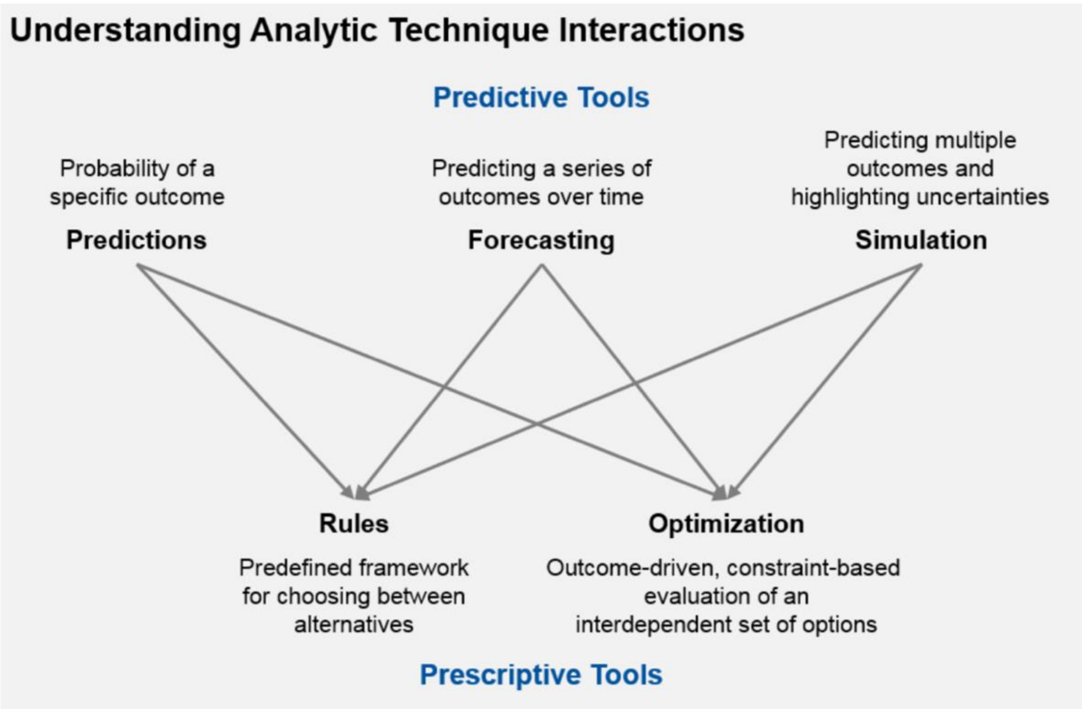


Figure 5 Predictive and prescriptive tools leading to simulation with reference to (Allega & Norton, 2018, p. 4).

Figure 5 illustrates the relationships across these specific types of tools, predictive and prescriptive, noting where simulation becomes essential, would provide an excellent opportunity to improve decision making by helping to build good expectations. While predictive analytics generally deals with probabilities of specific outcomes, forecasting (predicting a series of outcomes over time) and simulation (predicting multiple outcomes and highlighting uncertainties). Prescriptive analytics differs by facilitating a better understanding of how to influence the anticipated outcome. Thus, combining predictive analytics with prescriptive ones would extend predictive insights. It is essential to embrace more advanced analytics techniques when seeking to expand the analytics capabilities, as well as moving beyond the foundational approaches, e.g., diagnostic and descriptive, which would explore a move toward simulation. An excellent suggested way to generate actionable recommendations and proactive insights is by employing predictive and prescriptive analytics. Whereas, the first type spans several techniques, such as simulation, as well as optimization and business rules (Allega & Norton, 2018).

Simulation and modeling tools can also extend predictive and prescriptive analytics beyond optimization only. Tools in this space use advanced analytical modeling techniques to consider multiple outcomes within highly uncertain contexts across discrete event business processes, agents and the continuous flow of both within a system-of-systems framing (Allega & Norton, 2018).

4. Digital Trends and Digital Twin Technology

4.1. Digitalization or Digitization

"Digitization" and "Digitalization" are in fact two conceptual terms that oftentimes used interchangeably in a wide range of literature, but actually each of them has a precise meaning when used for the analytical purpose, and it is essential to distinguish between these two terms in this case (Brennen & Kreiss, 2014).
According to (Brennen & Kreiss, 2014), The Oxford English Dictionary (OED) (Simpson & Weiner, 1989) outlines the first uses of these two terms in conjunction with computers to the mid-1950s, where digitization refers to "the action or process of digitizing; the conversion of analogue data (esp. in later use images, video, and text) into digital form." Digitalization refers to "the adoption or increase in the use of digital or computer technology by an organization, industry, country, etc."

As per (Macchi, Roda, Negri, & Fumagalli, 2018, p. 793), digitization is "a transformation process that leads to plenty of opportunities. It enables the introductions new KETs in various engineering and management applications." (Key Enabling Technologies (KETs) such as the cited IoT, Big Data, advanced simulation, and others).
Digitalization has been defined in Gartner IT Glossary (Unknown, 2019) as "the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business."

Digitalization allows us to work smarter and more efficient. Besides, it provides a safer and greener place; sensors provide input to systems that improve maintenance solutions. Moreover, cloud solutions grant easy access to documents/files plus documents/data sharing. E.g., in a subsea operation, the engineering team can perform real-time analysis and make better decisions while utilizing real-time video signals transferred from the ROV.
The way of perceiving and interacting with technology is undergoing a radical transformation. There is a rapid increase in using digital representations of physical objects and organizational processes to analyze, monitor and control real-world environments. Moreover, the combination of new digital technologies, artificial intelligence (AI), and immersive experiences are setting the stage for open, connected and coordinated smart spaces (Cearley & Burke, 2018).

4.2. Industry 4.0

In (Ustundag & Cevikcan, 2018), the term Industry 4.0 (the Fourth Industrial Revolution) is presented as the new industrial revolution which (if not the most popular) is one of the most popular topics among respected industrial and academic communities. Industry 4.0 plays a crucial role in strategy, aids to utilize the digitalization opportunities of all the production phases. This revolution includes the combination of numerous physical and digital technologies including cloud computing, artificial intelligence (AI), augmented reality (AR), adaptive robotics, additive manufacturing and Internet of Things (IoT). The term, Industry 4.0, encounters a broad range of several concepts such as increments in mechanization and automation, networking, digitalization and miniaturization (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014). One of the essential purposes of industrial transformation, Ustundag and Cevikcan (2018) describe, is the ability to increase the efficiency and productivity of resources, therefore increasing companies' competitive power.

It can be described that the current transformation and interconnected era is extraordinary and different from others. By presenting service-driven business models, it illuminates the concept of smart and connected products. Besides it provides a subsequent change in main business processes, where interconnection links several key players such as employees, customers, partners and systems to speed up the business performance, optimizing processes and creating new opportunities to be mobilized on a shared platform (Ustundag & Cevikcan, 2018). Moreover, new categories of firms recently born, thus, adopting new particular roles within the manufacturing process (Lasi et al., 2014).

Digital Twin (DT) is one of the main concepts associated with the Industry 4.0 wave; it is an essential term nowadays. It has been nominated, as per (Cearley & Burke, 2018; Panetta, 2017), as the Trend No. 4 on Top 10 Strategic technology trends for 2018 as well as for 2019.

A consistent theme called the "intelligent digital mesh", which has been tagged along with Gartner´s strategic technology trends for the last two years in addition to 2019, will be further explained in detail in the next section.

4.3. The Intelligent Digital Mesh

The term "Intelligent Digital Mesh" has been described in (Cearley & Burke, 2018; Panetta, 2017), as the entwining of people, devices, content and services. This can be found by a broad combination of digital models, business platforms and a rich intelligent collection of services in order to support digital business. In more details, it is as following:

- **Intelligent:** This theme examines AI (Artificial Intelligence), with a specific emphasis on machine learning and gets into virtually every existing technology. Additionally, using AI for well-defined and scoped purposes can help to create better systems (e.g., more flexible, dynamic, and independent). It is expected that the main focus among technology providers through 2022 is going to be the development and utilization of AI.

- **Digital:** This theme main focus is on how digital and physical worlds are blending, leading to creating an immersive digitally developed and connected environment. Due to the rapid increase in the amount of data that can be produced, computing power is slipping to the edge to deal with the stream data and sending summary data to central systems. In other words, the digital trends and new opportunities have been enabled by AI, leading and controlling the coming generation of digital businesses, in addition to the creation of digital business ecosystems.

- **Mesh:** This theme refers to benefit from links and connections between an expanding set of people, businesses in addition to services alongside devices and content in seeking to deliver the digital business outcomes. The mesh requires new capacities and abilities which help to decrease the friction, providing in-depth safety and security, over and above, responding to events crossways these connections.

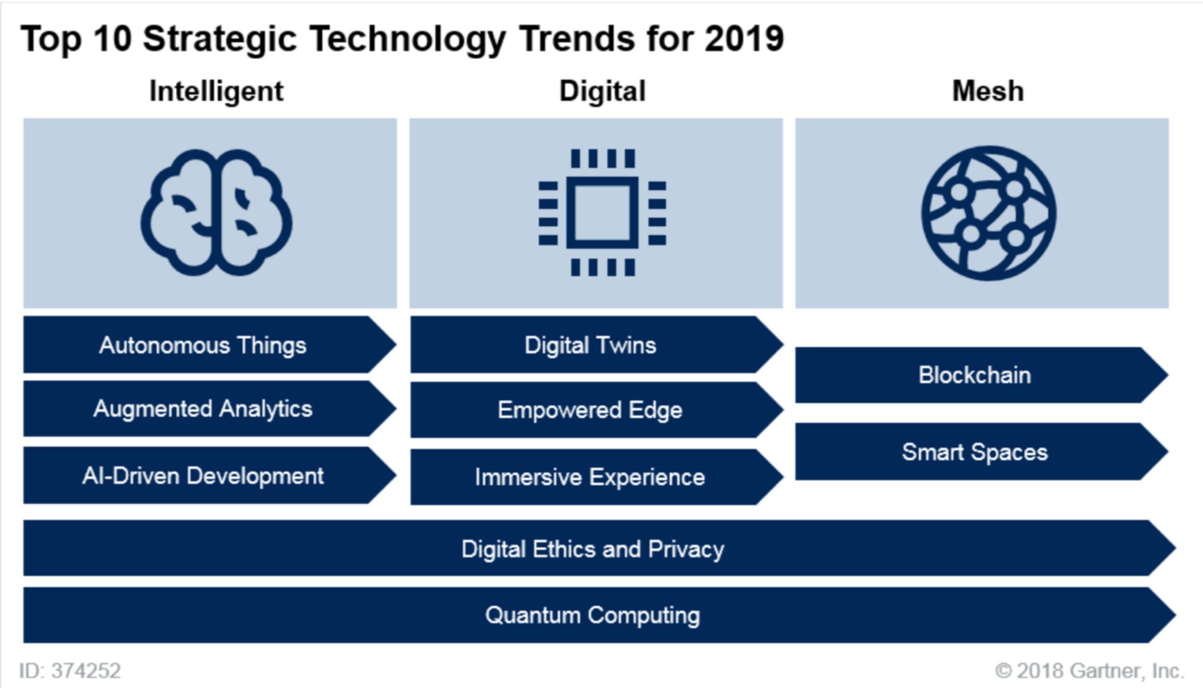


FIGURE 6 TOP 10 STRATEGIC TECHNOLOGY TRENDS FOR 2019, WITH REFERENCE TO (CEARLEY & BURKE, 2018, P. 5).

With reference to Figure 6 and to (Cearley & Burke, 2018; Panetta, 2017), the DT has been nominated as the Trend No. 4 for 2018 as well as for 2019. Whereas, an estimation of around 21 billion connected sensors and endpoints by 2020, DT might exist for billions of things. Cearley and Burke (2018) further point out that billions of dollars of savings in maintenance repair and operation (MRO) and optimized IoT asset performance are on the table.
Thence, digital twin will be further explained in detail in the next sections.

4.4. The Digital Twin

4.4.1. Digital twin definitions

The DT is a nascent technology, its definitions and capabilities are not systematically understood. Thus, standards and best applications are not well outlined yet. However, some of the many definitions for the DT are listed in Table 3 below.

The first definition of the digital twin by NASA:		
•	"An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. It is ultra-realistic and may consider one or more important and interdependent vehicle systems."	(Glaessgen & Stargel, 2012, p. 7; Negri, Fumagalli, & Macchi, 2017, p. 941)
General definitions:		
•	"It is the virtual and computerized counterpart of a physical system."	(Kritzinger, Karner, Traar, Henjes, & Sihn, 2018, p. 1016)
•	"A digital twin is a digital replica of a living or non-living physical entity."	Wikipedia ("Digital twin," 2019)
In terms of engineering:		
•	"A unified system model that can coordinate architecture, mechanical, electrical, software, verification, and other discipline- specific models across the system lifecycle, federating models in multiple vendor tools and configuration-controlled repositories."	(Bajaj, Cole, & Zwemer, 2016, p. 1)
•	"Ultra-high-fidelity physical models of the materials and structures that control the life of a vehicle."	(Reifsnider & Majumdar, 2013, p. 1)
•	"A virtual representation of the real product."	(Schroeder, Steinmetz, Pereira, & Espindola, 2016, p. 12)
In terms of the purpose of the digital twin:		
•	"The DT can be considered as a virtual entity, relying on the sensed and transmitted data of the IoT infrastructure as well as on the capability to elaborate data by means of Big Data technologies, with the purpose to allow optimizations and decision-making."	(Macchi et al., 2018, p. 790)
In terms of the role of the digital twin:		
•	"Digital twin is an integrated multi-physics, multi- scale, and probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin."	(Tao et al., 2018, p. 3564)

•	"Digital replications of living as well as nonliving entities that enable data to be seamlessly transmitted between the physical and virtual worlds."	(Saddik, 2018, p. 87)
•	"Digital representations of physical products or systems that consist of multiple models from various domains describing them on multiple scales."	(Vrabič, Erkoyuncu, Butala, & Roy, 2018, p. 139)
In terms of manufacturing:		
•	"The DT consists of a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and real system, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration. The topical role within Industry 4.0 manufacturing systems is to exploit these features to forecast and optimize the behavior of the production system at each life cycle phase in real time."	(Kritzinger et al., 2018, p. 1017; Negri et al., 2017, p. 946)
•	"Very realistic models of the process current state and its behavior in interaction with the environment in the real world."	(Rosen, Von Wichert, Lo, & Bettenhausen, 2015, p. 567)
•	"Coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge."	(Lee, Lapira, Bagheri, & Kao, 2013, p. 41)
In terms of aviation industry:		
•	"A cradle-to-grave model of an aircraft structure's ability to meet mission requirements, including sub models of the electronics, the flight controls, the propulsion system, and other subsystems."	(Tuegel, 2012, p. 1)
•	"Ultra-realistic, cradle-to-grave computer model of an aircraft structure that is used to assess the aircraft's ability to meet mission requirements."	(Gockel, Tudor, Brandyberry, Penmetsa, & Tuegel, 2012, p. 1)

TABLE 3 DEFINITIONS OF DIGITAL TWIN

It is noticeable after reviewing previous definitions that DT does not have a unique definition. One reason could be that it is not only associated with a specific sector. It was first applied in the aerospace field by NASA, and it was implemented in robotics afterward. In a while, it started to spread around in the manufacturing domain, as well as many different industries (Macchi et al., 2018; Negri et al., 2017).

After reading a broad of literature about the DT and its definitions, the following definition is one of the most used so far. It can be noticed in most of the literature (such as websites, articles, books, and so forth), it is the one which will be highlighted here as the simplest one, and therefore it can be used for any purpose in any industry:

- "A digital twin is a digital representation of a physical object." (Natis et al., 2017, p. 3).

4.4.2. The digital twin concept

It can be noticed that digital twin adaptation is on the growth. This concept has been defined for the first time in 2002 by Michael Grieves, in the context of a presentation about the product lifecycle management (PLM) (Kritzinger et al., 2018). However, in literature, there is no common or agreed understanding concerning this term. It has been used slightly different over the disparate disciplines. As previously mentioned, DT is a digital representation of a physical system or product that consists of many models from different domains and describes them on different scales. Both DT and its physical twin are supposed to be changing and evolving together throughout their lifecycle. The added value to different phases in a project life cycle by the integrated models has been demonstrated extensively. This is usually facilitated by allowing extensive evaluation of performance in both the design and planning phase in addition by obtaining real-time reflection with the physical counterpart during the operation phase (Vrabič et al., 2018). DT first recognition has already been realized and captured as expected in the aerospace world in the form of NASA Technology Roadmaps (Kritzinger et al., 2018; Negri et al., 2017). The understanding of the DT concept varies and still is incomplete due to the multiple solutions and ideas of this term that exist across all related industries (Kritzinger et al., 2018; Tao et al., 2018).

In reality, applying DT has already started well before sorting out the technical prerequisites for its implementation. The first concept of DT conceived as a virtual product "a rich representation of a product that is virtually indistinguishable from its physical counterpart". As per previous concept, the real and the virtual counterparts connect together by tying data throughout the project's lifecycle. However, there is fast and enormous progress in this concept on all levels from managing technology to the way of collecting data in addition to the digital representation (Vrabič et al., 2018, p. 139).

As per (Natis et al., 2017), the digital twin implementation, as shown in Figure 7, is an encapsulated software object which reflects or, I.e., mirrors the characteristics of the physical object or the collection of physical objects.

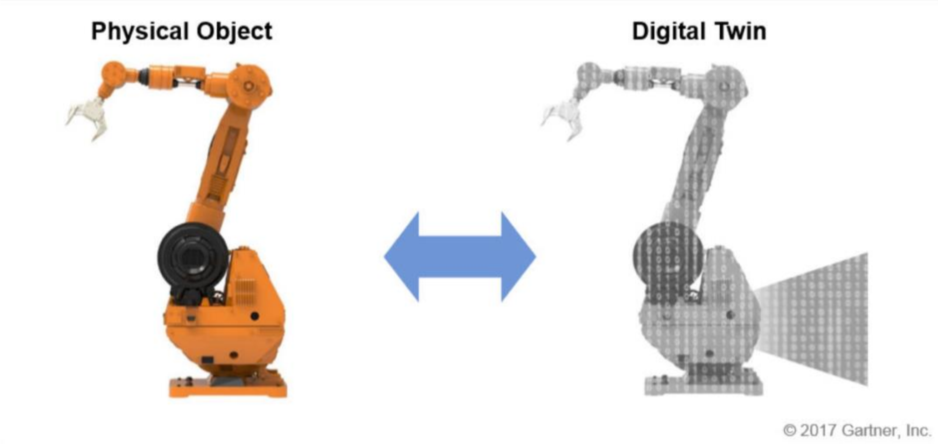


Figure 7 A digital twin concept, with reference to (Natis et al., 2017, p. 3).

Kritzinger et al. (2018) point out that it is highly important to distinguish between the three different terms: Digital Model (DM), Digital Shadow (DS) and Digital Twin (DT). The noticed results in this paper illustrate that not enough literature concerning DT currently available as it is in the highest development stage, yet more literature can be found about the DM and the DS. Even though the three terms are often used synonymously. Whereas the main difference between those three terms is related to the level of data integration between the physical and digital counterparts while some digital representations are modeled manually and there is no connection with any physical object, in fact, others are completely integrated with real-time data exchange.
Therefore, a classification of these three subcategories, according to the data integration level, is briefly explained, as shown in Figure 8, with reference to (Kritzinger et al., 2018, p. 1017), as follow:

- **Digital Model:** "A Digital Model is a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital object." I.e., this type of digital representation might and might not include a sufficient, comprehensive description of the physical object and the change in the state of the physical object has no direct effect on the digital object and vice versa.

- **Digital Shadow:** Referring to the definition of the Digital Model above, in cases where further automated one-way data flow between the existing physical object state and the digital object state exists, this type of combination should be called Digital Shadow. I.e., the change in the state of the physical object produces a change in the state of the digital object but not vice versa.

- **Digital Twin:** In cases where there is a complete integration in both directions in data flow between the existing physical object and the digital object, then, this type of combination is referred to as digital twin. Moreover, the digital object can act as a controlling instance of the physical object in DT. It is possible to have other physical or digital objects, which result in changes of state in the digital object. I.e., the change in the state of the physical object directly produces a change in the state of the digital object and vice versa.

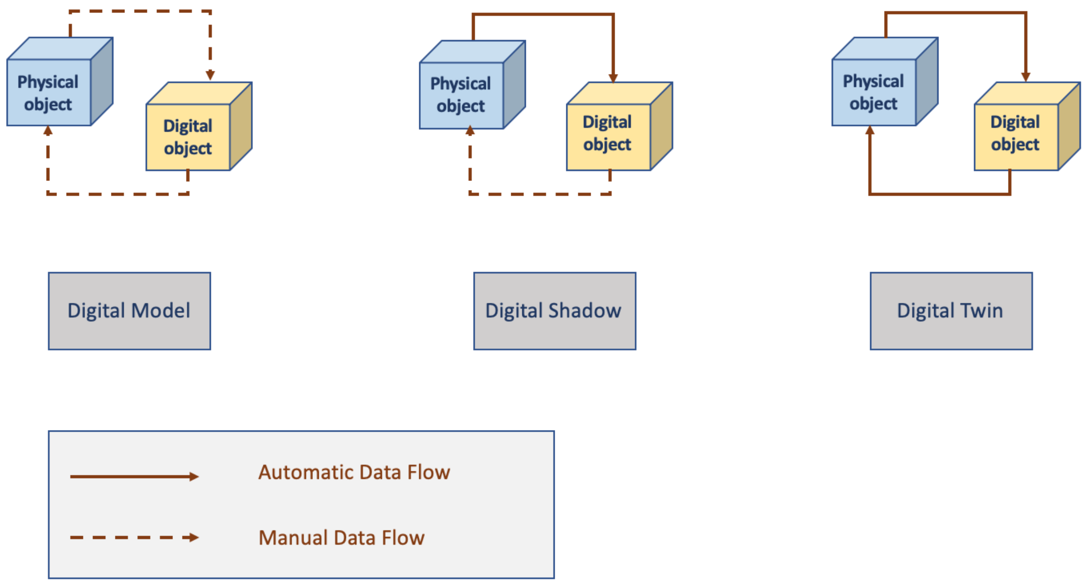


FIGURE 8 THE DATA FLOW IN THE THREE SUBCATEGORIES OF A DIGITAL TWIN, ADJUSTED FROM (KRITZINGER ET AL., 2018, P. 1017)

4.4.3. The digital twin characteristics

DT has the following characteristics, as Saddik (2018) explains:

- **Unique identifier:** This characteristic signifies the communications between the digital and physical counterparts imposes that each DT should have a unique identifier.
- **Sensors and actuators:** This characteristic implies that the physical counterparts would be equipped with sensors to allow the digital counterpart to replicate their five senses (sight, taste, smell, hearing, and touch) by employing the correct actuators based on application requirements.
- **AI:** This characteristic denotes that it is necessary that DT is equipped with a controller embedded with ontologies and machine learning in addition to deep learning techniques that increases the ability to make quick, intelligent and appropriate decisions on behalf of the real twin.

- **Communication:** This characteristic implies that it is imperative that DT would be able to interact in real-time with the entire environment and real counterpart in addition to other digital twins as it is illustrated in Figure 9. Communication (including the sense of touch/haptics) must occur within 1 ms, therefore must follow 5G as well as Tactile Internet standards.

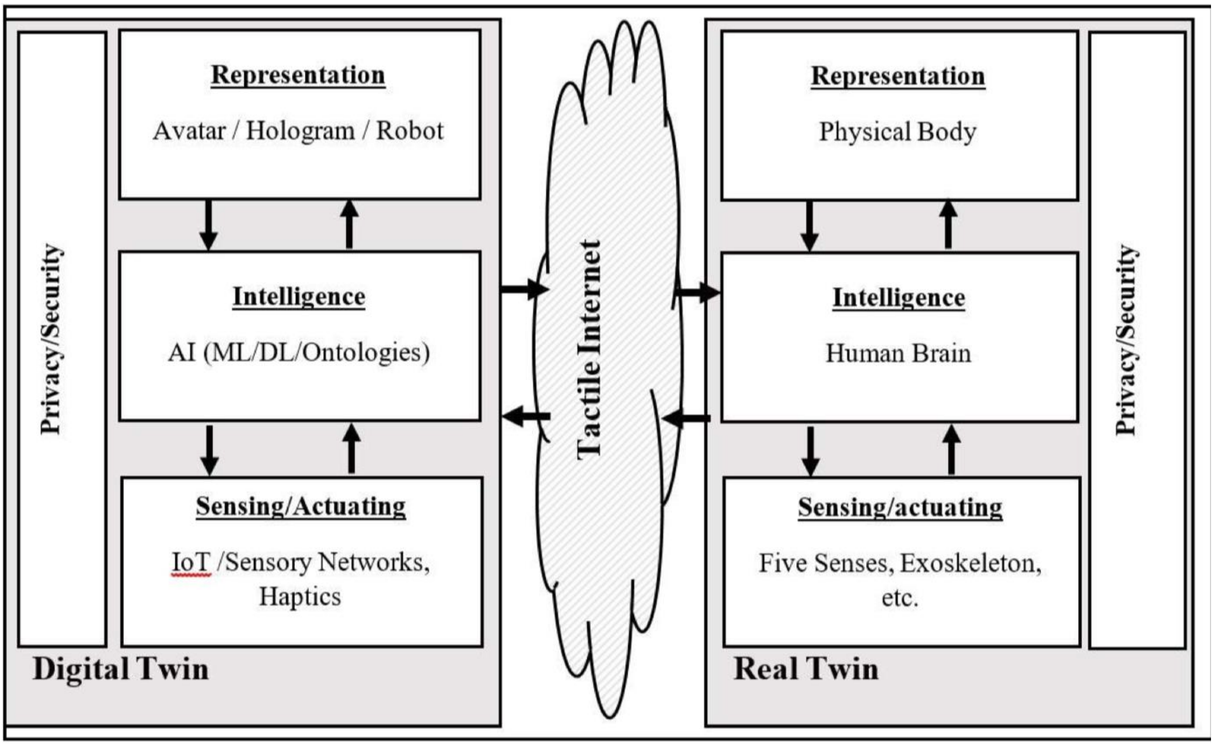


FIGURE 9 THE INTERACTION AND COMMUNICATION BETWEEN REAL AND DIGITAL COUNTERPARTS, WITH REFERENCE TO (SADDIK, 2018, P. 88).

- **Representation:** This characteristic indicates that it is possible that DT has a virtual representation such as a 3D avatar, hologram, or a humanoid social robot. This representation might be simpler such as software components without a tangible representation. All of that is based on the application, which has an essential role in deciding the needed representation type.

- **Trust:** This characteristic implies that DT might handle sensitive and critical tasks, for instance, managing a stock portfolio or financial transactions. Moreover, DT might interact on behalf of its physical twin, meaning that the real counterpart should trust its digital counterpart.

- **Privacy and security:** This characteristic signifies the necessity that DT would have the ability to protect the identity and privacy of its physical counterpart. Thus, it is vital to apply advanced cryptography algorithms and biometrics techniques such as haptic biometrics, ECG biometrics, etc. In addition to the resolution of regulatory and political issues.

4.4.4. Why digital twin

Utilizing IoT technologies in digitalization is increasing through time. In this context, DT concept is the latest innovation that can be implemented and employed into monitoring in order to make informed decisions about the actual physical things, their state, their context in addition to apply required actions in order to optimize their future state. (Natis et al., 2017)

DT will drastically have direct involvement in IoT projects since it can provide high operational awareness of the physical objects of a project which will help achieve better decisions associated with the changing state of such objects. Further implementations such as high-value-asset industry sectors (transportation, manufacturing) and mission-critical sectors (aerospace, defense) where instrumenting and modeling complex things such as machines, pumps, cars, aircrafts and spacecraft can be very useful to increase the return on investment (ROI) for such projects and increase the physical objects performance beside reducing operational risk, (Cearley & Burke, 2018; Natis et al., 2017), and Figure 10 below.

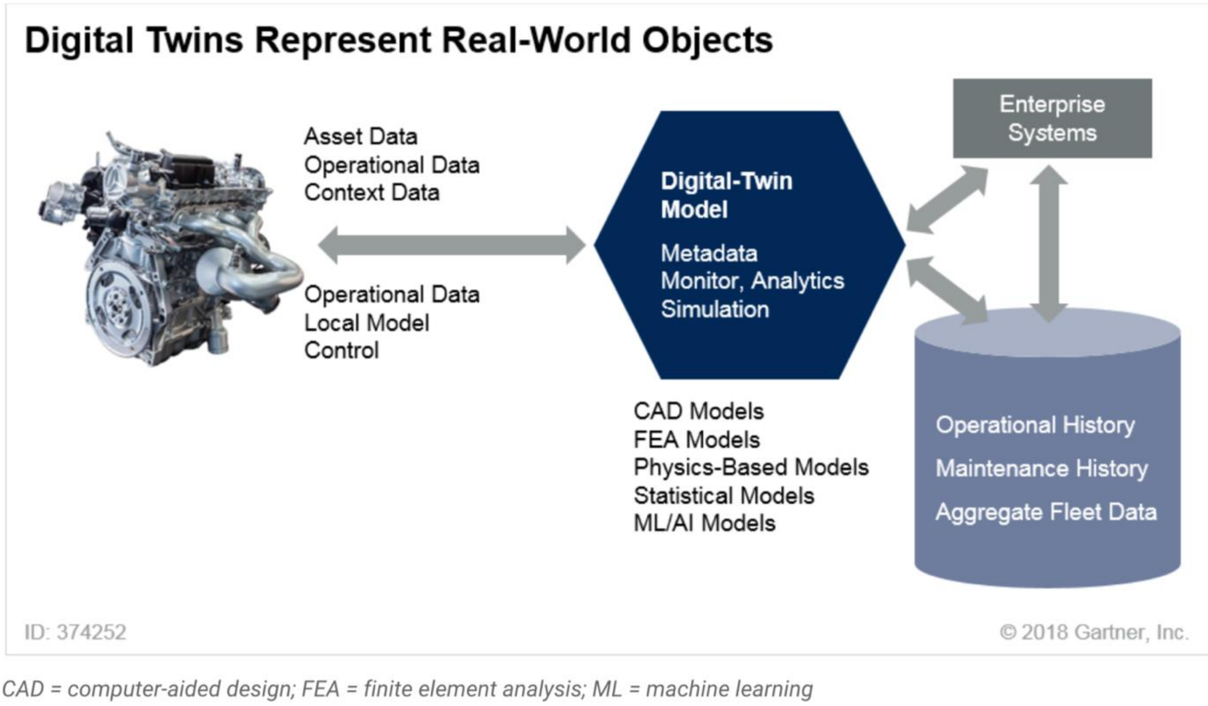


FIGURE 10 DIGITAL TWINS ARE DIGITAL REPRESENTATION OF THE REAL WORLD OBJECTS, WITH REFERENCE TO (CEARLEY & BURKE, 2018, P. 18).

Operators can utilize DT models to improve asset maintenance mode from a traditional protective and preventive maintenance schedules to a prognostic and predictive condition-based one. This can have a direct impact on operational costs in addition to capital expenditure (CAPEX) by extending the life of these objects. Moreover enhancing assets performance due to increase the ability to control maintenance schedule (Natis et al., 2017).

Additionally, Wildfire (2018) defines DT as “a virtual model of a process, product or service”. As further explains, pairing of physical and virtual worlds can be applied in different stages and cases for different objectives. For instance, to be ahead off problems before their appearance by using data analysis, system monitoring and simulation for future plans which will lead to reduction in downtime to minimal.

DT in the long term might facilitate the growth of new business models, e.g., objects’ charging based on performance data, selling physical object-related performance data or even selling elements of DT for new approaches such as how to drive service-based or performance-based business operations (Natis et al., 2017).

DT can be very advantageous in the manufacturing business. It is full of promises regarding the lifecycle of assets management by increasing productivity, competitiveness and efficiency, especially when supporting the following main disciplines of the production systems (Kritzinger et al., 2018):

1. **The production planning and control:** (Macchi et al., 2018; Rosen et al., 2015)

    - Enhanced decision-making when pointing on more details and predicting the performance and behavior of the system in the long-term.
    - Automatic planning and execution following orders from the units of manufacturing
    - Optimizing the system control software and checking its feasibility.
    - Simulating the instrumentality of IoT devices.
    - Statistically- based decision-making and optimization, for instance, optimizing the performance and behavior of the system when applying simulation to all the lifecycle phases (with the awareness of the past and present states).

2. **The maintenance:** (D’Addona, Ullah, & Matarazzo, 2017; Macchi et al., 2018; Susto, Schirru, Pampuri, McLoone, & Beghi, 2015)

    - Identifying changes´ impact on all types of processes in the production system.
    - Identifying and evaluating possible preventive maintenance measures.

- Improving maintenance decision-making, for instance, prediction of cracks and damages with physical systems reliability modeling.
- Valuing the states of machines by using machine learning algorithms in addition to some unique descriptive methods.

3. **The layout planning:**

- Valuing and planning the production system.
- Automating and applying independent data acquisition and variation.

The rating of DT is as trend no. 4 between the top 10 strategic technology trends for 2018 (Panetta, 2017) and for 2019 as well (Cearley & Burke, 2018), strategic technology trends can create considerable disruption and deliver great opportunities. Usually, these top trends have been evaluated by the leaders of enterprise architecture and technology innovation in order to identify opportunities, counter hazards and find new competitive characteristics.

4.4.5. The digital twin elements:

DT is the new tool that will have an essential role in decision-making processes associated with physical products. This will improve the situational awareness in traditional analytical approaches. Besides, it will allow better responses to changing conditions, especially for asset optimization and preventive maintenance. DT, by using the most suitable software tools, renders real-world objects digitally, so it has the ability to directly monitor them and sometimes even control the physical object. In this context, to produce a digital twin, there are four required elements in addition to three optional elements as well (Natis et al., 2017).

The minimum elements of a DT, as shown in Figure 11, and with reference to (Natis et al., 2017), are as follows:

- **Model:** The model can be described as the building brick starting point for a digital twin.

  - The model may have elements such as the model data structure, metadata (relational/physical) beside the functional elements system models or the critical variables (pressure, temperature, and so forth).

  - DT inputs can come from different models such as CAD models, simulation models, functional models of a physical object, as well as manufacturing bill of materials (BOM) models.

  - Two modifications to the model can be implemented:

1. The model can be extended: In order to create a more vibrant representation of the real-world physical object. It is considered a good practice to enrich a digital twin by adding extra model elements and data.
2. The model can be expanded: In order to have a more complex, composite digital twin assembled from simpler atomic digital twins, which will make it more valuable, useful and beneficial. E.g., an "atomic level" digital twin of the advanced driver assistance systems (ADAS), or the anti-lock braking system (ABS) which can be integrated into the composite digital twin of the car; thus, it shows the relevant ADAS or ABS detail for the vehicle as appropriate.

- **Data:** The data from the DT has two aspects:

1. Data that comes directly from the physical object: this data can identify events, time series, class, instance, etc. This can include different types of data such as status data (e.g., if the valve is on or off), sensor data (e.g., the pressure) or event data (e.g., alerts in case of an item has exceeded its threshold).
2. The data that is contextual for the object: this data can provide some additional information related to the object (e.g., maintenance logs, supply chain, weather data, etc.).

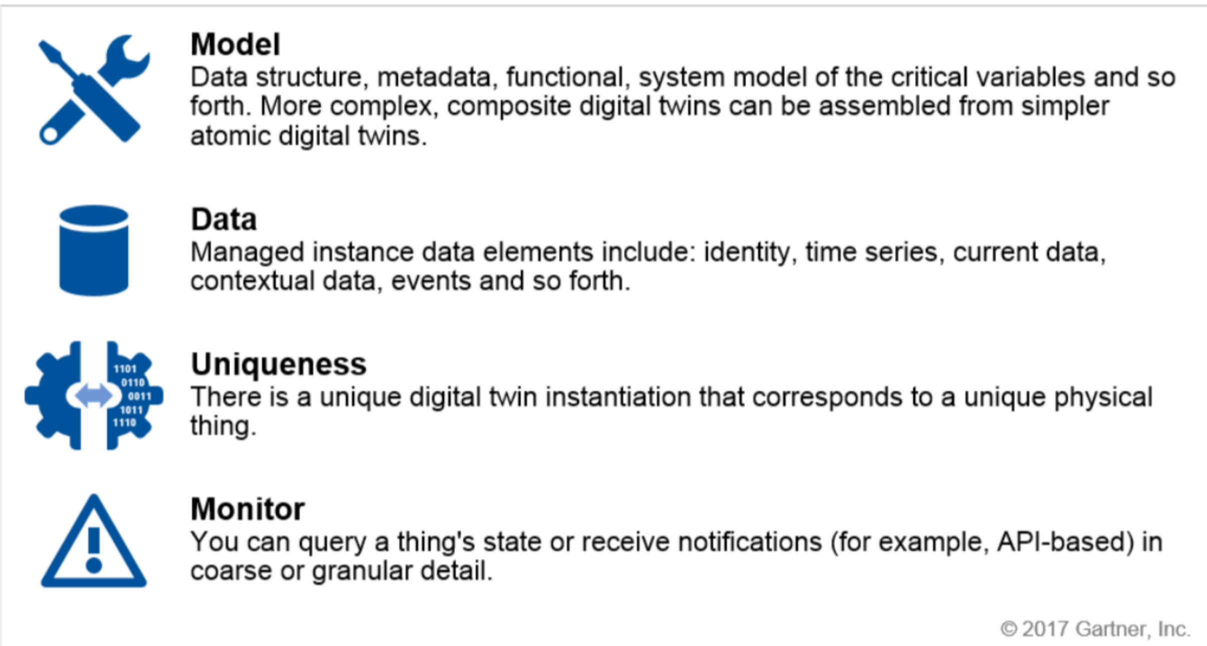


FIGURE 11 REQUIRED ELEMENTS FOR A DIGITAL TWIN, WITH REFERENCE TO (NATIS ET AL., 2017, P. 4)

- **Uniqueness:** DT uniqueness means that e.g. one digital twin can represent only one crane though, it is not possible that it represents more than one. This means that a one-to-one correspondence will be between a digital twin instance and only the specific physical object that it connects to. Therefore, the first step is to construct a model for the digital twin based on the obtained information after checking and specifying the enterprise objectives. The next step is to generate an instance, which aligns with the unique identity of the real-world thing and its data in order to create a unique digital twin eventually.

From another perspective, it is possible that the same object has more than one digital twin in order to meet the diverse needs. E.g., a car may have a digital twin to meet the different needs of the car´ manufacturer and of the car´ owner. Moreover, in the case of a composite or an extended digital twin, the uniqueness will be composed of the unique subsystems and components of which the complex "thing" is comprised. In other words, from the DT perspective**,** there is a one-to-one correspondence, while there might be a one-to-many correspondence from the physical object perspective.

- **Monitor:** The DT can monitor the relevant aspects of the physical object state, in addition, to receive notifications based on preset parameters. To be more clear on this element, if the DT is considered as an envelope around the data, any application that requires to send data into the object or to read data from the object has to access the data using the DT.

As shown in Figure 12, and with reference to (Natis et al., 2017); additional (optional) elements can be added to the digital twin depending on business objectives and technical requirements, that includes:

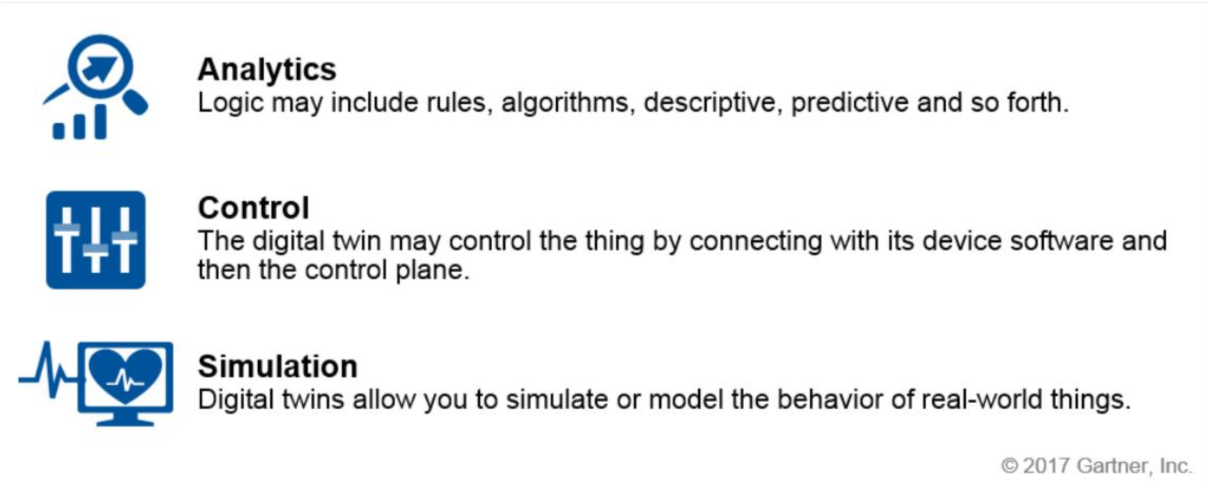


FIGURE 12 OPTIONAL ELEMENTS FOR A DIGITAL TWIN, WITH REFERENCE TO (NATIS ET AL., 2017, P. 5).

- **Analytics:** The DT logic might include some rule engines or even complex-event processing, which are applied to incoming IoT data. However, these logic elements could generate triggers or alerts, which coordinate the workflow and the different forms of descriptive analytics in order to identify the cases of exceeding thresholds.
- **Control:** This feature will not always be available. Also, not all digital twins will have this ability to control an object. However, if it is available, they will connect through the specific control system of the object. It is expected that direct control will be exposed via some form of digital-twin API, which is executed by authorized software on a machine-to-machine basis. This is not limited to this technique only; some other techniques can be used for direct control as well (by using an augmented virtual reality app, or a mobile app).
- **Simulation:** It is possible to use the DT to model the current and/or the future behavior of an object. This can be done by using different sets of configurations and conditions, in addition to many other applications, such as identifying optimum schedules for operation or for maintenance, anticipating optimal operation modes or failures and so forth.

4.4.6. Entities and applications of digital twins:

There is a broad range of entities that might have DT, from things, processes, people and places to complex environments such as enterprises, cities or even countries. However, the most mature used cases tend to focus on people and things, with reference to (Natis et al., 2017; Saddik, 2018):

- **Things:** It is spanning the simple to very complex and it is being built progressively in order to meet the consumer or the enterprise objectives.
- **Processes:** In general, processes focus on physical objects such as the optimization of a production pipeline in manufacturing. This type of DT might be assembled from several atomic digital twins (e.g., the case of the production pipeline process, one composite digital twin may combine all the different digital twins from individual production pipelines and represent the whole production process). It has become highly noticeable the increase in utilizing new models for business processes.
- **Human:** In this type of digital twin, a model for a categorized group of persons would be created and delivered based on interactions and demands. E.g., building a new model in a bank for its customers based on transactions. The main focus in such models is all about understanding the behavior and state of the person, in addition to helping craft inputs and modify their behavior in order to meet other objectives such as enhancing safety or healthcare which might be one of the most potent applications of DT.

- **Places:** This type of model is increasingly becoming very critical, especially for mobile objects in a wide range of use cases either for consumers or enterprises, e.g., bridges and parking spots.
- **Complex objects:** The main objective of this type of DT is to meet decision-making processes, e.g., financial.

Subsequently, the DT benefits and implications are not only limited to the manufacturing domain. It exceeds to include health, social life and so on. As Saddik (2018) additionally advocates, DT could have a significant role in the well-being of detecting stress levels employing sensory technology and determining the reasons behind the stress. By utilizing intelligent algorithms, DT could compute the physical twin´ pattern of stressful situations and therefore suggest some recommendations and advice about the suggested ways to increase or avoid stress.

Other applications of DT can vary in a broad range from financial management to e-learning, online social interactions in addition to virtual shopping tours and so on. In many such applications, there is a need to have a highly personalized DT, so it could be effective when interacting on behalf of the real twin with other persons or/and other digital representations. As Saddik (2018) states, all the current media options such as videos, photos and sound recordings have a better role in helping us holding onto the past and recalling people and moments than our memories.

4.4.7. Key technologies to make DT:

Saddik (2018) explains that the support of several key technologies is necessary in order to realize DT, such as:

- **Augmented, virtual, and mixed reality:** In order to create DT, it is possible to employ 3D technologies and display them as a hologram or maybe utilizing AR/VR/MR devices such as Microsoft HoloLens, as illustrated in Figure 13. As an example, in the case, a person is in sitting at his office at work and his son is sick at home, using sensors installed at the office to generate his real-time digital twin and appear at home as a hologram in front of his son in order to comfort him. Therefore, it makes the interaction between people from different locations possible just the same as if they were in the same space.

FIGURE 13 A SUBJECT INTERACTING WITH THE HOLOGRAPHIC REPRESENTATION OF HIS DIGITAL TWIN, WITH REFERENCE TO (SADDIK, 2018, P. 89).

- **Haptics:** Integrating haptic properties by DT could enhance communications. For instance, when a person (e.g., Mark) shakes hands with the DT of another person (e.g., Maria), this DT can provide proper haptic feedback to Maria.

- **Robotics:** Humanoid, in addition to the soft robotics technologies can be leveraged to help DT physically act on behalf of the real physical counterpart.

- **5G and Tactile Internet:** The appearance of the 5G and Tactile Internet are seeking to deliver ultra-low-delay and ultra-high-reliable communications. The appearance of these technologies has facilitated a paradigm shift from conventional content-oriented to control-oriented communication, especially for human-in-the-loop applications which are highly delaying sensitive in addition to the demand for tight integration of communication and control mechanisms. Thus, DT would provide an always-active twin feedback loop that develops the physical systems service quality.

- **Cloud computing:** Digital twins are more scalable because of offloading computation and control to cloud computing infrastructures. Furthermore, it can be guaranteed that they are available to support their physical twin anytime and anywhere.

- **Wearables:** This technology is attractive to many different users. However, these devices could collect every day an amount of physiological data that can be hired by DT to provide better support for its physical counterpart.

- **Internet of Things:** The IoT can be used to feed the contextual data from users to their DT. Therefore, feedback can be sent to the environment, facilitating a better and smoother interaction between users and their surroundings as well as remote locations.

- **Artificial Intelligence:** The IoT data is processed by using algorithms that are constantly improved with applying updated user data. When using this type of time-series data, a digital twin user could easily suggest actions that can help with controlling and monitoring or even avoiding potentially harmful situations.

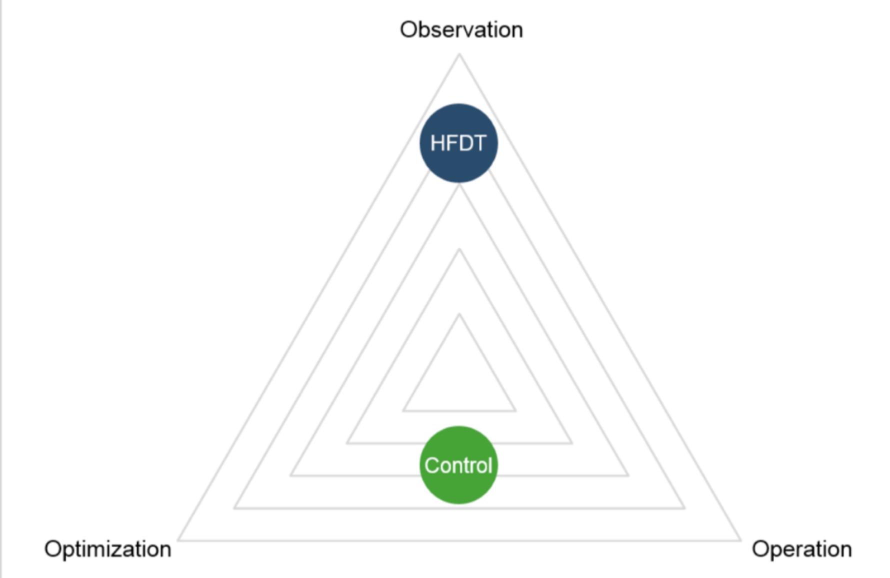
4.4.8. Categories and Roles of DT:

The main focus when employing digital twin is on meeting specific business objectives, optimizing return and minimizing cost. This can be done when the DT utilizes an optimized approach and choose the correct technology foundations. As shown in Figure 14 and with reference to (Natis et al., 2017), the DT roles are as follow:

1. **Operation model:** In this model, the physical objects, such as valves or lamps, will have a degree of control by implementing e.g., remote-control capabilities, and therefore setting parameters for the object, e.g., the room temperature.

2. **Optimization model:** In this model, a simulation model will be built by employing different building block techniques, e.g. CAD and finite element analysis, in addition to establish the basic critical parameters for the DT model of the object. Thence, the data collected from the object along with the model and the contextual data will run simulations in order to optimize predictions of the object' performance and providing modified actions in the system, e.g., optimizing the pitch of the blades can increase the output of a wind farm.

3. **Observation model**: This model can be a passive monitoring one by receiving data streams of one object which is used in the monitoring task of another object state or feeding into the subsequent development of the thresholds of the digital twin. This can be done by most digital twin types. The most important thing is to provide collected sufficient data, then it would be easy to analyze it and to identify key thresholds, in addition, to issue special workflows coordination when deviations exist.



HFDT = high-fidelity digital twin

FIGURE 14 CATEGORIES AND EXAMPLES OF DT, WITH REFERENCE TO (NATIS ET AL., 2017, P. 8)

It is further explained in (Natis et al., 2017), that it is essential to identify the business function required from the digital twin and develop the suitable type for different cases. Therefore, in a situation when a project' objective is to set up an unlock feature on a connected door lock, the focus in the elements of the digital twin should be on engagement of the control system for that door and less on historical data or complex modeling. Whereas, in the case when a project' objective is to produce optimal power from a wind farm, operational capacities will be the important elements in that case, in addition to the ability to incorporate historical data, the individual windmills state, contextual data (e.g., forecasts and weather conditions), etc.

DT can also be a hybrid model able to leverage a blend of these roles. This point will be illustrated in the two following examples, with reference to (Natis et al., 2017):

High-fidelity physics model: A high-fidelity physics model or HFDT usually requires to have a stronger simulation element, in addition to incorporating contextual historical data with control and monitor model elements. Such a model might have been constructed by using limited element analysis or maybe other computational methods in order to model the physical objects and to identify critical failure points or key inputs which will be observed. These inputs data or any related contextual data are going to feed into simulations which usually take an essential part in the decision-making process. This type of model, such as HFDT or extremely accurate medical patient model, is generally extremely high in cost, which makes its usage quite limited. Therefore, it can be used in cases with high potential impact for both human life as well as cost to the organization, and sometimes for the type of objects that are very expensive and difficult to get to during operations.

Control digital twin: A control digital twin, based on the defined state of the object, can engage the control system of the asset and the trigger action (e.g., Is the object on or off? Is the window open? Is the water level below a certain defined threshold?) It might include a blend of operation and optimization roles based on business objectives. Assets, such as lights, would usually be included in a mostly operation role´ control digital twin when users of such models would need to acquire specific information about the asset (e.g., is the asset on or off, or empty or full) based on these information and on the case itself, some parameters will be changed then (e.g., turn it off).

From another side, with reference to (Batty, 2018), in the smart cities context. Wildfire (2018) distinguishes between two types of cities:

- The first one is <u>the high-frequency city</u>, which should operate in real-time at the same level of the same correct periods, second by second, minute by minute, gradually up to cycles of days and months, and so forth.

- The second one is <u>the low-frequency city,</u> which should operate over the years, decades, centuries, and so forth.

In other words, different models are built in seeking to explore very short time horizons, This is called <u>reactive digital twin</u> in which real-time (or near real-time) interventions and smooth day-to-day running of the city are improved by visualizations and feedback, whereas in <u>predictive digital twin,</u> precise input data are employed to make better long term scenario planning to direct the best investment decisions. Batty (2018) additionally argues that it is important to (sometimes) turn the digital twin offline so it can be used to find out how the real system can be improved.

4.4.9. Digital twin and risk

Although digital twins help a lot with driving better decisions, it is important to take into consideration several crucial risk sources that might exist when using digital twins, which include with reference to (Kutnick & Velosa, 2017; Natis et al., 2017; Porter & Heppelmann, 2015; Shetty, 2017):

- **Complexity:** Digital twins are quite complex to be developed, this level of complexity might not be required in some business problem cases, where it might be more adequate to simply use ordinary control systems and acquired sensor data without using this complex physical model for controlling and monitoring.

- **Integration:** A challenge with integration will be encountered in any environment with a moderate level of heterogeneity in its physical objects. The reason is that there is still no uniform design approach to implement DT to be used when having a heterogeneous set of assets (e.g., objects of varying levels of complexity and age, and sometimes from multiple retailers.

- **Experience:** DT is a nascent technology; therefore, there is a lack of experience and knowledge about DT. Furthermore, just a few enterprises can provide this technology and have knowledgeable people, skills, policies and methodologies in order to develop digital twins.

- **Cost:** It is costly for an enterprise to develop the required DT model, implement it in the business, in addition to organize training courses for employees from different departments and backgrounds to utilize it properly. This cost might exceed the payback from its benefits. It is recommended to conduct a cost-benefit analysis and make sure of having a positive Return on Investment (ROI) in the standard time frame for the projects.

- **Security:** Cyber security could be a challenge when developing a DT. A comprehensive review should be carried out in order to reduce the difficulties that might occur, such as opening a vector into a physical object control system and that therefore will pave the way for hackers to damage enterprise objects as well as putting lives at risk. Digital twins, likewise, most of the smart connected products, have significant new points of vulnerability. Thus, the impact of intrusions can be more severe. For instance, it is possible that hackers could take control of a product or tap into the sensitive data that moves between it, the constructor, and his client. I.e., the risk raised by hackers breaking into connected products (such as automobiles, aircraft, generators, or even medical equipment), could be far greater than the risk posed by hacking a business e-mail server.

- **Perspective:** The perspectives on the design, functionality, and usage of DT might differ between different parts of the enterprise, which could create challenges and obstacles when implementing the DT. Also, when defining the valuable data and DT boundary management.

- **Privacy:** Many questions are rising regarding constructing a DT in some particular cases, for example, creating a DT for an organization or probably for a person. It is still not clear when that starts to tread on privacy laws and concerns, for instance, would have a digital twin which is showing the location and other workflow capabilities of a unionized technician raise concerns? Or, would having just the model of a human be a privacy violation? Those types of questions are not answered yet; thus; there is a big discussion about associated risk. Or in other words, utilizing digital twin capabilities may expose enterprise and customer data to privacy, usage model and data ownership questions that may create significant reputation, compliance or legal vulnerabilities and issues for CIOs, business executives and even the board of directors.

4.4.10. The current status of DT

Many global corporations have already announced their digital-twin capabilities, such those representative providers, as per (Natis et al., 2017) include:

- **Amazon:** An essential element of its whole wide Amazon Web Services (AWS) IoT architecture is "device shadow", which its role is as a communication layer between applications and devices connected to AWS IoT. Amazon company has built vacuum cleaners' functional models, pipeline equipment, etc.

- **LogMeIn:** The company has a Xively device avatar, which is a functional digital twin, this DT helps the company to establish records for individual objects and thus into enabling business processes and data management.

- **SAP:** They have already several digital twin-initiatives. It has a high-fidelity physics set of capabilities by acquiring Fedem Technology. Furthermore, SAP has the potential to construct functional and lower-fidelity digital twins for objects like power drills, compressors, and so forth.

- **Siemens:** Siemens has extensive experience in physics, graphics and simulation, in addition to the renowned software capabilities, which includes Teamcenter and MindSphere IoT, the firm leverages all of that to develop digital twins. It has a great history of creating digital twins for products, production processes as well as asset operating status to encounter the needed level of fidelity and therefore to predict physical performance.

5. Digital Twin Versus Simulation Modelling

This Chapter aims to introduce learnings after reading and reviewing the broad range of literature about simulation modeling and digital twin, thus will be done by:

- Illustrating the link between the digital twin concept (DT) and the simulation modeling concept (SM).
- Performing a general comparison between SM and DT.
- Generating a broad discussion, from a risk analysis perspective, of the differences between DT and SM.
- Summarizing the concluded results in Table 4 at the end of the Chapter.

Simulation seems to be a key aspect related to the digital twin concept, which is nascent. Therefore, different perspectives and ways of linking digital twin to simulation modeling could be identified.

One perspective is that digital twin approach is the next wave in modeling, simulation and optimization technology. As Rosen et al. (2015, pp. 567, 568) describe and as Figure 15 illustrates, there is a recognizable evolution regarding the simulation technology over the last decades which has taken the course through the following four waves:

- The first wave- Individual Application- from 1960 to 1985- when simulation was just a limited technology for very particular subjects (e.g., to specialists, professionals, and computers).

- The second wave- Simulation Tools- from 1985 to 2000- when simulation was just a standard tool that was hired to help solving specific design engineering problems (by engineers).

- The third wave- Simulation-based System design- from 2000 to 2015- when simulation was utilized as the basis for decisions by allowing a structured approach to multi-level and multi-disciplinary systems with an enhanced variety of implementations (e.g., design decisions for complete systems).

- The fourth wave- Digital Twin Concept- from 2015 until now- when simulation represents an essential functionality being utilized to provide support along the whole life cycle of a system (e.g., using the real-time data to support operation and service).

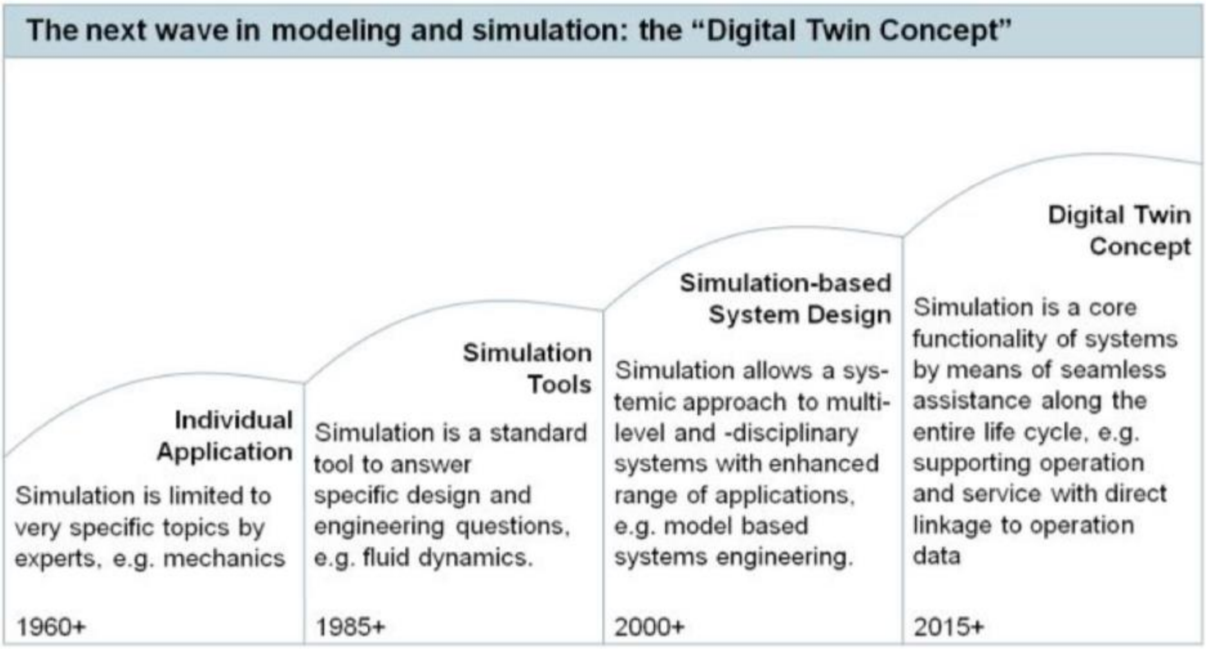


FIGURE 15 THE DIGITAL TWIN AS THE NEXT WAVE IN SIMULATION TECHNOLOGY, WITH REFERENCE TO (ROSEN ET AL., 2015, P. 568)

However, "communication by simulation" is the core concept of model-based systems engineering (MBSE) which is considered the rising trend in systems engineering. Furthermore, simulation mostly is widely considered as a tool for R&D (Research and Development).
At the present time, digital twin which is recognized as the new wave of this development is the core system/product functionality along the lifecycle phases (which can be, e.g., either delivered before the real product in the planning phase, or used as a supporting tool in the construction and operation phases) (Rosen et al., 2015, p. 568).

Another perspective, as Negri et al. (2017, p. 943) describe: "is the intimate connection to simulation, that is seen in two different ways:

1. DT as a model that represents the system that different types of simulations can be based upon.
2. DT as the simulation of the system itself."

In another meaning, currently, there is no unified way of defining the connection or the differences between simulation modelling and digital twin yet. However, different purposes and characteristics that link the two concepts could be identified among available references on this subject. Still that differs depending on many factors such as the author background, the domain or the industry, etc.

5.1. Comparison digital twin versus simulation modelling

There are many arguments and questions about DT as mentioned earlier, for instance, is it really a new technology? What are the differences between digital twin and simulation modeling? Why would it be important to have a digital twin and what benefits can it provide?

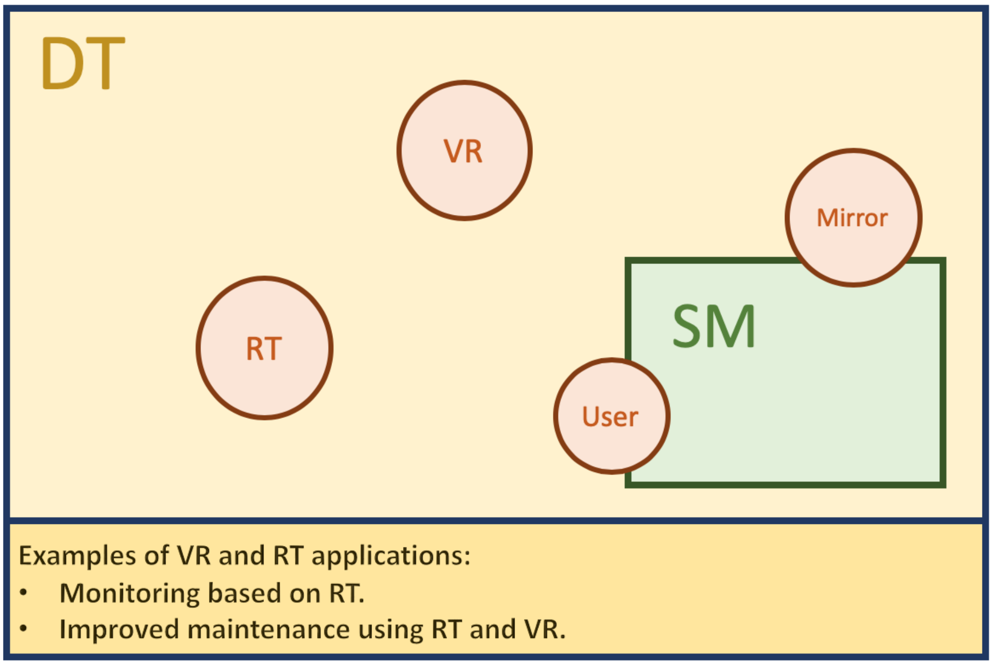


Figure 16 Main differences between DT and SM

After reviewing the two previous Chapters 3 and 4, many differences could be found between DT and SM, the main ones, as shown in Figure 16, are as follow:

1. **User:** (Atea, personal communication, April 2019)
   While SM would require particular expertise to be able to interpret and utilize the obtained results in further applications such as carrying out a risk analysis.
   DT requires no particular high expertise in order to interpret, use, or check outputs, results, alarms and so forth.

2. **Virtual Reality (VR):** (Atea, personal communication, April 2019)
   While Virtual Reality is not available as a feature in SM. It is part of DT, as mentioned earlier in Section 4.4.2, the first concept of DT conceived as a virtual product “a rich representation of a product that is virtually indistinguishable from its physical counterpart” (Vrabič et al., 2018, p. 139). Moreover, Negri et al. (2017) explain in manufacturing, DT research is an evolution of ongoing researches regarding Virtual

Factories (VF). DT even goes beyond VF by employing real-time synchronization (which is the next feature in this list) with the physical system, which by utilizing the available data (historical and current) would assist into making better decisions regarding production.

3. **Real time:** (Batty, 2018; Jackson, 2019; Atea, personal communication, April 2019)
   While simulation may replicate what could happen in the real world, but not what is currently happening.
   DT can provide the exact match of the processes operating the real system in real-time.

4. **Mirror:** (Batty, 2018)
   While models are defined as simplifications of the real thing, therefore, the aim of models is not to deliver a complete mirror to the original system in all detail as that system, which makes the model intrinsically different from the original system.
   DT can provide a close to the exact match of the processes operating the real system in real-time.

The mentioned above differences would have many relevant and useful applications that are not available in SM but would be in DT, a further instance of this is:

- Monitor Tool builds on real-time data: (Atea, personal communication, April 2019)
  Simulation modeling can be used for monitoring, but since it does not provide the RT feature, monitoring on real-time data is not available in SM, while this is available in DT, it is thus one of the potential main applications areas of DT.
  DT can help to monitor some aspects of the physical object state, and thus to receive notifications based on preset parameters (Natis et al., 2017), a further instance of this, is to monitor cases such as fatigue and abnormalities in the physical twin, moreover to monitor geometric and plastic deformation on the physical twin materials (Negri et al., 2017).

- Improved maintenance: (Atea, personal communication, April 2019)
  This is one of the most critical applications for DT using the VR and RT features, as described earlier with more details in Sections 4.4.4 and 4.4.5 improving asset maintenance mode from a traditional protective and preventive maintenance schedules to a prognostic and predictive condition-based one (Natis et al., 2017). Moreover, this could be very beneficial from the cost perspective, where dynamic service agreements could replace the static ones.

5.2. Digital twin versus simulation modelling from risk analysis perspective

The discussion in this section is mainly based on (Aven, 2015), the literature found in Chapters 3 and 4, as well as the concluded differences in Section 5.1.

As explained earlier in Chapter 3, risk analysis could be carried out at any phase of a lifecycle of a project, system, or similar. The main driver to conduct a risk analysis is to support decision-making, which is one of the main objectives of DT technology not only risk-related decisions, but also those, which are part of a broader vision. Another reason to conduct a risk analysis is to obtain the basis of which evaluation and comparison of different solutions can be performed. DT could be beneficial in such cases, to help in performing evaluations and comparisons by utilizing both historical as well as real-time data. In addition to run simulations alongside testing them using VR. This could provide more solid evaluations and comparisons that could produce trusted and worthy results. In general, as Shetty (2017) explains, the traditional analytical approaches would become more valuable when using digital twins as DT can improve situational awareness, and enable more appropriate responses to changing conditions, especially for optimizing asset and preventive maintenance. This would represent a great support while conducting risk analysis providing a clear guidance for decision making for maintenance cases.
Additional gains and benefits can be addressed when carrying out risk analysis; such as providing the support in finding the right balance between different concerns and choices (e.g., cost and safety). However, when the focus is on risk description with dimensions including uncertainty and consequences, conditions and factors which are covered by risk calculations could be brought out. Risk analysis should also express the likelihood associated with the occurrence of events. Employing machine learning when utilizing DT would raise its accuracy and precision be associated with a lower likelihood and therefore better chances for an acceptable risk level.

As explained in details in Chapter 3, there are two main types of risk analysis, quantitative and qualitative. Quantitative Risk Analysis is a model-based risk analysis, aims to estimate the risk in the form of probability of a loss such as simulation modeling. Monte Carlo simulation specifically represents an alternative to analytical calculation methods, in which it is easier to handle the time aspect than in an analytical method. MC has been utilized for decades to help out while carrying a risk analysis. One of the main attractions to Monte Carlo simulation model is that it might be an adequate representation of the real world. Moreover, MC outputs are usually informative and comprehensive. However, the main disadvantage of Monte Carlo simulation from a risk analysis perspective, as Aven (2015, pp. 82, 83) describes, is time and cost associated with implementing and developing the model. Due to all its characteristics, Digital Twin could be the new competitor of MC in the area of risk analysis. As it has been presented in Chapter 4, DT represents a mirror for a physical project, process, system or similar that can be used to run simulations. Usually, it should be matching the physical twin which is taking place in real-time, and therefore this could be understood as if digital twin is the new generation of development of simulation modeling.

Employing DT can help on lowering both; cost of operating as well as potential capital expenses, Due to ability to extend the object life (the object which they represent) and optimize the asset performance while it is operative. However, DT can be used for controlling, monitoring, and making informed decisions regarding the actual physical things' context and state, and thus taking actions that help optimizing their future state.

The comparison of DT Vs. SM, in Section 5.1, was conducted for seeking answers to many questions about DT including what is new and what differs this technology from SM. What makes DT important in the industry, what benefits could it provide and so forth. However, many differences can be identified yet; the two essential differences between DT and SM are:

- Virtual Reality (VR).
- Real Time (RT).

Having these two features together as well as utilizing the available (historical and current) data in addition to the machine learning could be very useful when risk analysis is carried out. Risk analysis gives a risk description that could be used as a basis for decision-making regarding the choice of solutions, by helping to identify the crucial contributors to risk as well as outlining the impact of possible measures on risk. This could be done easier, faster and more accurate when employing all mentioned above, at the same time. For example, when utilizing DT in the construction phase of a project, an improved risk description could be obtained, better explained and easier understood by clients when using VR for scenario testing.

Moreover, VR feature represents a great added value for making choices; it helps a lot in making smarter choices using less time. This applies to maintenance as well, where VR could be very beneficial and useful. Having the option of walking around and getting an insight virtually to any facility or sector could be very helpful to improve the quality of getting the task done, by reaching the aimed results as well as saving time.
RT feature helps by providing real-time data and therefore using this data for smarter and more accurate choices, as well as saving time. I.e., if the available data is accurate and more reliable, the probabilities derived from it, when carrying out risk analysis, would be certain and therefore provide accurate predictions of future events. This could be very beneficial to assess different scenarios spontaneously and therefore perform risk analysis for shorter periods in short time using historical data in addition to the real-time data, and still get trustful results with fairly low uncertainty.

Furthermore, these two features could have new applications, such as monitoring and maintenance.
DT provides a monitoring tool built on real-time data in addition to VR feature. It provides the ability to monitor some aspects of the physical object state based on preset parameters.

This works as a barrier indicator, or as a predictive key risk indicator, by deploying an alarming system or similar. This will be described in more details in Chapter 7; Section 7.1, where a case-study will be developed to show how it can be implemented on a real case from a real system applying DT in order to maintain a healthy working environment. Generally, the analysis expresses risk for the total activity, system, and so on, the risk thus should be reflected in relation to specific areas, factors, groups, etc. While usually, risk analyses focus on expected values and probabilities, as well as factors that influence the outcomes.

One more difference between DT and SM is the user feature which means that unlike simulation, no particular expertise nor very high technical skills in order to interpret and utilize the results are required. This is important and very useful when performing a risk analysis since usually utilizing special methods and models to perform analysis demands considerable effort and resources to develop suitable models and therefore, to express the risk. Additionally, the cost involved in such cases is not necessarily in proportion to the usefulness of the analysis. Whereas, DT could be used with no requirement to find a special risk analyst with special qualifications, therefore carrying out risk analysis in less time and higher quality without the need for added cost for a specialist.

Another additional advantage of DT is that it can provide a close to exact match of the processes operating the real system in real-time, which could help to get accurate predictions when carrying out a risk analysis with lower uncertainties.

An essential additional application of DT is that it improves asset maintenance mode. For example, from a traditional protective and preventive maintenance schedules leading to a prognostic and predictive condition-based one, furthermore, dynamic service agreements could replace the static ones, and this is very beneficial from the risk analysis perspective since this could help in reducing failures (as consequences), as well as reducing maintenance expenses, therefore managing operational risk. I.e., the use of risk analysis to support decisions on maintenance, risk acceptance and risk-informed decision-making.

Finally, it is expected that the new mentioned features in DT would help a lot in enhancing risk analysis during the life cycle of a project. This could be justified by referring to what Aven (2015, pp. 156, 157) states about the possibility of carrying out risk analysis even in cases when access to a large amount of historical data is not possible, but in such cases it would be difficult to establish good predictions, besides the large uncertainties. DT with all new extra characteristics especially real-time data and VR, would support conducting risk analysis, and therefore establishing high predictions with small uncertainties using rapidly generated data combined with historical data, and thus establishing reasonably good predictions, accompanied by non-high uncertainties.

Table 4 provides a summary of all the described differences above between DT and SM, as well as the link between each feature and risk analysis, how it helps to enhance risk analysis and in which direction.

	Feature	Simulation Modelling	Digital Twin	Risk Analysis	
				Application area	Benefits
1	**User**	Special expertise requirements	No requirements	-Risk analyzing team	-Cost -Time -Quality
2	**Virtual Reality**	Not applicable	Applicable	-Decision-making -Checking scenarios -Maintenance	-Time -Smarter choices
3	**Real Time**	Replication of what could happen, but not what is currently happening	Matching exactly the processes	-Risk analysis process -Decision-making -Maintenance	-Time -Smarter and more accurate choices -Certain probabilities -Accurate predictions -Low uncertainty
4	**Mirror**	Simplifications	Close to exact match	-Risk analysis process	-Accurate predictions -Lower uncertainties
Examples on applications:					
•	**Improved maintenance**	Traditional (RT and VR are not available)	Predictive	-operational risk -support decisions on maintenance -risk acceptance -risk-informed decision-making.	-Better consequences -Reduced failures -Reduced expenses -Dynamic service agreements
•	**Monitor on real-time data**	Monitor but not on RT data (RT is not available)	Applicable	-Risk indicator -Barrier indicator	-Safety -Time

TABLE 4 MAIN DIFFERENCES BETWEEN DT AND SM, THE LINK TO RISK ANALYSIS

The coming two Chapters will provide some practical cases that would help to a better understanding of some of the previous explained points.

First, in Chapter 6, an example of a simplified risk study to an office building DT is presented, by highlighting the opportunities and threats of different phases of its lifecycle, starting from the engineering phase, going through the construction phase and finally the operation phase. This example has been generated for a specific DT for the office building of Atea Stavanger in Sola, but it also applies to any other similar office building.

Second, in Chapter 7, various types of situations are covered, by developing three study-cases from different cases and applications of the same DT from Chapter 6. These cases would be utilized to address the usage of a digital twin in order to help in risk reduction in different phases of a project lifetime, in addition to present an example of a successful use of some applications of DT as a risk indicator tool as well as monitoring and controlling based on real-time data.

6. Overview of digital twin risks

6.1. Study system

This Chapter is about the specific digital twin for Atea AS office building.

Atea, as an ICT-company, provides solutions, products and services in IT infrastructure for businesses and public-sector organizations in Europe's Nordic and Baltic regions.

Atea Stavanger has recently moved into their new building allocated in Sola. The building has a Bream-excellent classification and is considered one of the smartest buildings in the world, with micro-powerplant, energy wells, solar cells, energy-storages, superior energy efficiency, smart offices, smart facility management and so forth.
As of the time of writing this thesis, a digital twin for this building is under development. The data is partially available, as the project is not finished yet.

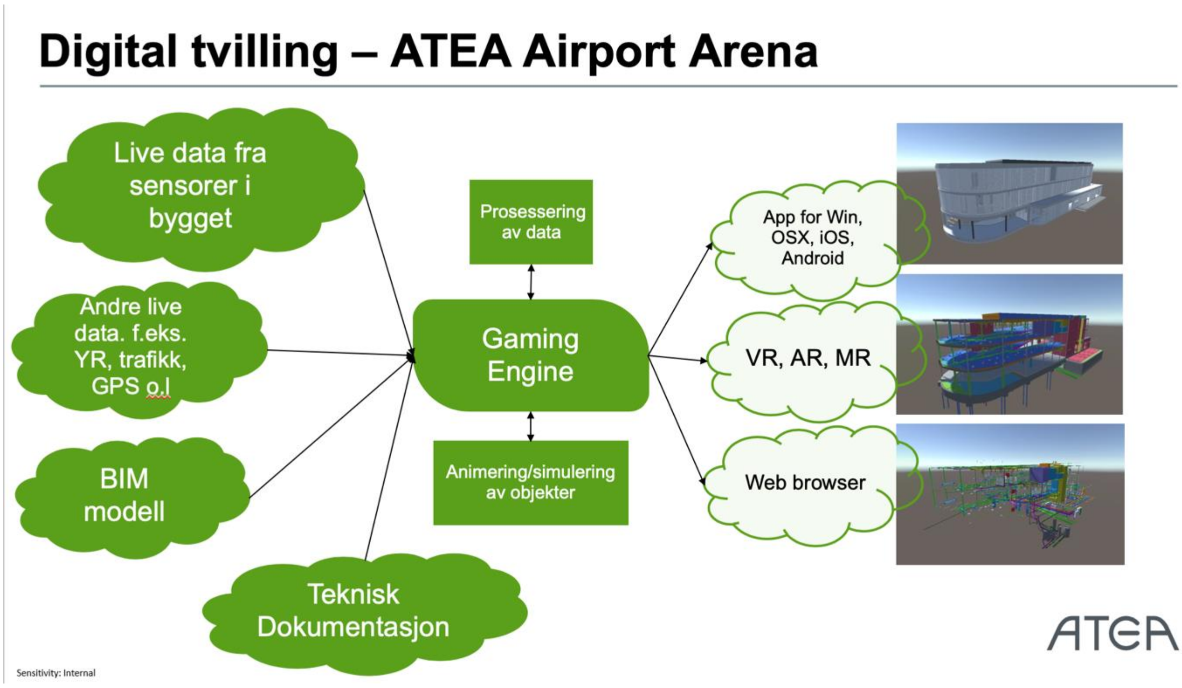


FIGURE 17 DIGITAL TWIN AS PRESENTED BY ATEA AS, (ATEA, PERSONAL COMMUNICATION, MAY 2019)

This digital twin, see Figure 17, is the one that will be used to develop the study-cases in Chapter 7, as well as in this Chapter.

As explained earlier, this digital twin is for a specific office building (Atea AS in Sola), but the following information in this Chapter are applicable to any other similar office building.

6.2. Risk analysis scope

A simplified risk study to the digital twin mentioned above will be presented in the following sections of this Chapter, in order to establish an initial picture of it. This broad risk analysis will be performed from an expansive point of view, as Aven (2015) describes, It covers both threats as well as opportunities, which would thus provide an overview of this digital twin risks and therefore a better general understanding before taking the specific cases in Chapter 7.

The example in this Chapter, as Figure 18 illuminates, is to provide a better understanding of both opportunities and threats involved when utilizing a digital twin in each phase of a similar project. As Aven (2015, p. 38) states "what you have not identified, you cannot deal with." In the case of an undefined event, it is hard to get its best benefits, nor to minimize or to avoid its consequences. Moreover, these opportunities and threats are different for each phase.

As Wasserman (2017) explains from a manufacturing point of view "For design, the twin's main purpose is to set the performance of the product for the lifecycle. For manufacturing, it's to optimize the process and reduce costs. For services, it is to reduce the operational cost and to use predictive methods. The idea is to bring simulation into this lifecycle information: you have a physical asset where you link it to a parallel Digital Twin." This point of view could be generalized on any field and therefore on our example here, as per Table 5:

Design phase	=>	Engineering phase:	Supporting decision-making, choosing the best alternative, and reducing cost.
Manufacturing phase	=>	Construction phase:	Optimization and cost reduction.
Service phase	=>	Operation phase:	Managing operational risk and using predictive methods.

TABLE 5 UNDERLINED APPLICATIONS OF DT IN EACH PHASE

As it has been explained earlier in Chapter 3, the conceptual framework for understanding and describing risk in this thesis is outlined by definition in Section 3.1.2, by the pair (C, U), where C is the consequences, U means that C are unknown. The consequences could be split into either way:

- Events A and consequences C.
- Risk sources RS, events A, and consequences C.

6.3. An overview study

The following three phases of the life cycle of the building project will be covered:

- Engineering phase
- Construction phase
- Operation phase

Identification of initiating events, as Aven (2015, p. 38) states, is a critical task of the analysis, it is thus significant to carry it out in a structured and systematic manner, as well as electing the right persons with good competence to handle this task.

In order to get this task done, a structured brainstorming in which some questions, as well as checklists, have been used to reach the results illustrated in Figure 18 and discussed in more detail in the following sub-chapters.

6.3.1. Engineering phase

This phase is the one prior to the construction phase, where the design is at least partly ready, and the opportunity to implement changes and discuss different solutions between the different responsible parties (e.g., designer, contractor, project owner, etc.) is still available.

6.3.1.1. Opportunities

Utilizing DT in this phase would introduce many opportunities; it is mainly about deciding the final plan and connecting all the project elements and items from all sections together (e.g., construction, electricity, infrastructure, pipelines, and so forth). In addition, better testing for the produced different scenario alternatives, especially by using the virtual visual model.

The highlighted opportunities are the following ones:

- Easy to change.
- Scenario testing.
- Visual virtual model.
- Ability to test solutions without construction cost.
- Increased effectiveness

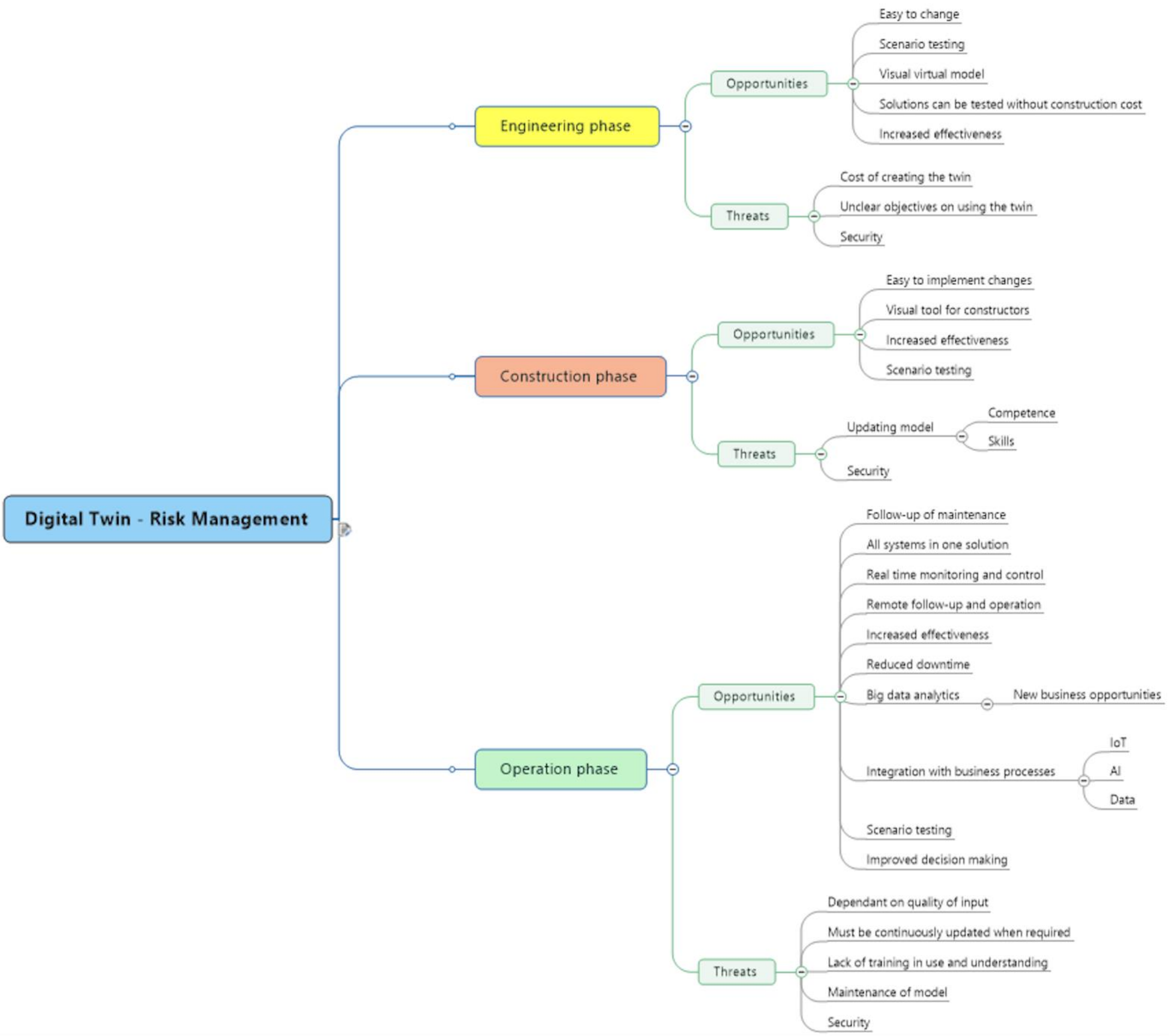


FIGURE 18 OPPORTUNITIES AND THREATS FOR DIFFERENT PHASES OF AN OFFICE BUILDING DIGITAL TWIN LIFECYCLE

6.3.1.2. Threats

As many opportunities would be introduced, many threats would be faced as well when using DT in this phase, such as:

- Cost associated with creating DT: This is the first problem require to be thought through. As it is an added cost for a company to develop the required DT model, and it requires a sort of a guarantee that the cost in this phase is in proportion with the obtained benefits, this will be explained later by the case-study in Chapter7, Section 7.3.

- Clarity of the objectives on using DT: What are the main requirements of DT in this phase? This question is a frequent one. The benefits of using DT in this stage are usually not very clear yet. It appears suddenly when a problem comes up. In this case, the importance of having a DT to avoid such problems becomes apparent. This will be discussed in more details in Chapter 7, Section 7.3, where a case-study illustrates the importance of employing DT in such cases.

- Data security: One of the main concerns in this stage is the security threat of using DT (data breach) in such an early stage. In regards of data sharing between different parties which would include conditional data at this stage.

6.3.2. Construction phase

This phase begins when on-site works starts. It is still quite flexible to do some changes in this phase; of course, not as it is in the previous phases. Moreover, many new difficulties and obstacles may occur in this stage while construction works are going on.

6.3.2.1. Opportunities

Mostly, opportunities for using DT in this phase are the same as the prior phase. It helps in providing better testing environment for the different scenario alternatives in addition to utilize the virtual visual model which would help constructors with better and easier understanding. E.g. having this option in the case study in Section 7.3 would be very useful to prevent that catastrophic result.

The main opportunities found for this phase are as follow:

- Easy to implement changes.
- Visual tool for construction workers.
- Increased effectiveness.
- Scenario testing.

6.3.2.2. Threats

The threats found in this phase are:

- Updating model: Certain competencies and skills would be required in order to update the model, which sometimes could be a challenge since this technology is considered as a nascent one.
- Security.

6.3.3. Operation phase

This phase begins when the project is complete and is already being utilized. Many people consider this phase, so far, the most important one to develop DT and employing it.

6.3.3.1. Opportunities

Much more opportunities could be presented over here since this phase is the one which the physical twin is ready and connected to its digital twin. In addition to the ability to use more features and characteristics of the DT, such as real-time data and so on, the first two study-cases in Chapter 7 are ones that will provide more detailed examples of this. Therefore, DT could be used for more objectives and in broader directions, as follows:

- Follow-up of maintenance.
- All systems in one solution.
- Real-time monitoring and control.
- Remote follow-up and operation.
- Increased effectiveness.
- Reduced downtime.
- Big data analysis.
- New business opportunities.
- Integration with business processes (IoT, AI, Data).
- Scenario testing.
- Improved decision making.

6.3.3.2. Threats

This phase is considered a dynamic phase and not only more opportunities, but more threats could also be enumerated. All of them are related either to data issues, experience, and skills as well as security.
The following threats for this phase have been found:

- Dependent on the quality of input.
- Must be continuously updated when required.
- Lack of training in usage and understanding.
- Maintenance of model.
- Security.

Obviously, security is considered as a threat included in all lifecycle phases. The reason behind that is that DT as most of the smart connected products, see Section 4.4.9, has significant new points of vulnerability, such as opening a vector into a physical object control system. This will open the way for hackers to damage enterprise objects, take control of a product, or tap into the sensitive data that moves between it, the constructor, and his client.

The following Chapter covers three study-cases of the same DT, to discuss in more detail some of the suggested points above.

7. Study Cases

This Chapter includes three different study-cases that are developed in cooperation with Atea AS.

The primary purpose of developing these study-cases is to manifest how a digital twin can help reducing risk in different phases of a project lifetime, operation phase (cases No. 1 & 2) and Engineering phase (case No. 3).

The same DT from Chapter 6 has been used in order to develop the following study-cases in this Chapter:

- Case-study No. 1: This case is from the operation phase. It illustrates the possibility of utilizing DT as a risk indicator tool which it would be, to control CO2 level in the building by using the data available for all the factors that affect CO2 level in order to modify it to the accepted level. This will be explained in more details in Section 7.1.

- Case-study No. 2: This case as well will be taken from the operation phase. It is meant provide a clarification about employing DT to provide good information for risk description when carrying out risk analysis and therefore provide support in decision-making. This will be explained in more details in Section 7.2.

- Case-study No. 3: This case is from the engineering phase, where the studied DT was not available yet. It should illustrate the importance of employing DT during this phase and to provide an example of an unexpected failure that could be avoided very easily if DT was available. This will be explained in more details in Section 7.3.

By the end of the Chapter, a summary of the three study-cases will be presented in Table 8.

Atea AS building digital twin engine:

As a start, it is crucial to clarify in a simple way the studied DT of the building, how does the system work and how is it connected.

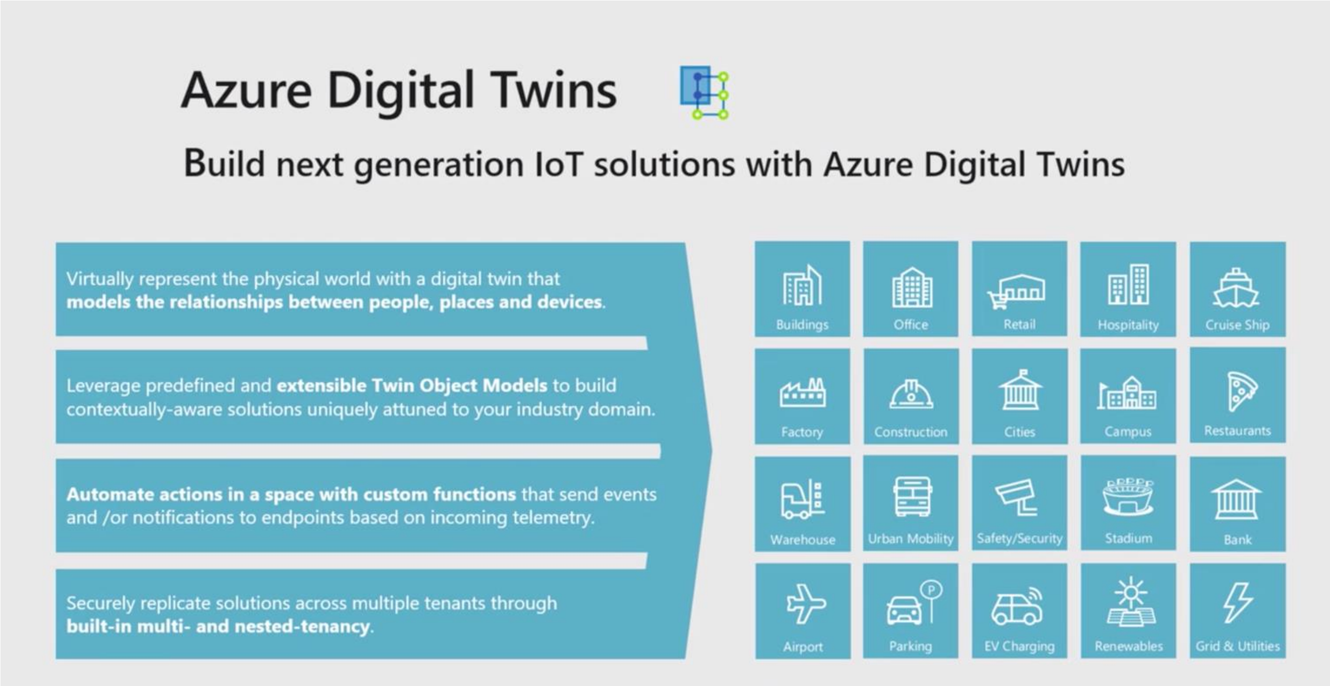


FIGURE 19 AZURE DIGITAL TWINS, WITH REFERENCE TO (JULIESETO, 2019)

But before that, it would be essential to provide an explanation about Azure Digital Twins which Atea AS used and clarify what it is:
Azure Digital Twins is a new product from Microsoft, as Figure 19 illustrates. It is defined as: "An Azure IoT service that creates comprehensive models of the physical environment. It can create spatial intelligence graphs to model the relationships and interactions between people, spaces, and devices." (Julieseto, 2019).

As (Julieseto, 2019) and Figure 20 explain, Azure Digital Twins provide the ability to query data from a physical space instead of having to acquire data from several different sensors that would help to build highly scalable, reusable, spatially aware experiences which would help in linking streaming data across the physical and digital world. Some examples of how Azure Digital Twins utilized are to predict required maintenance, analyze real-time data, track daily temperature and so forth.

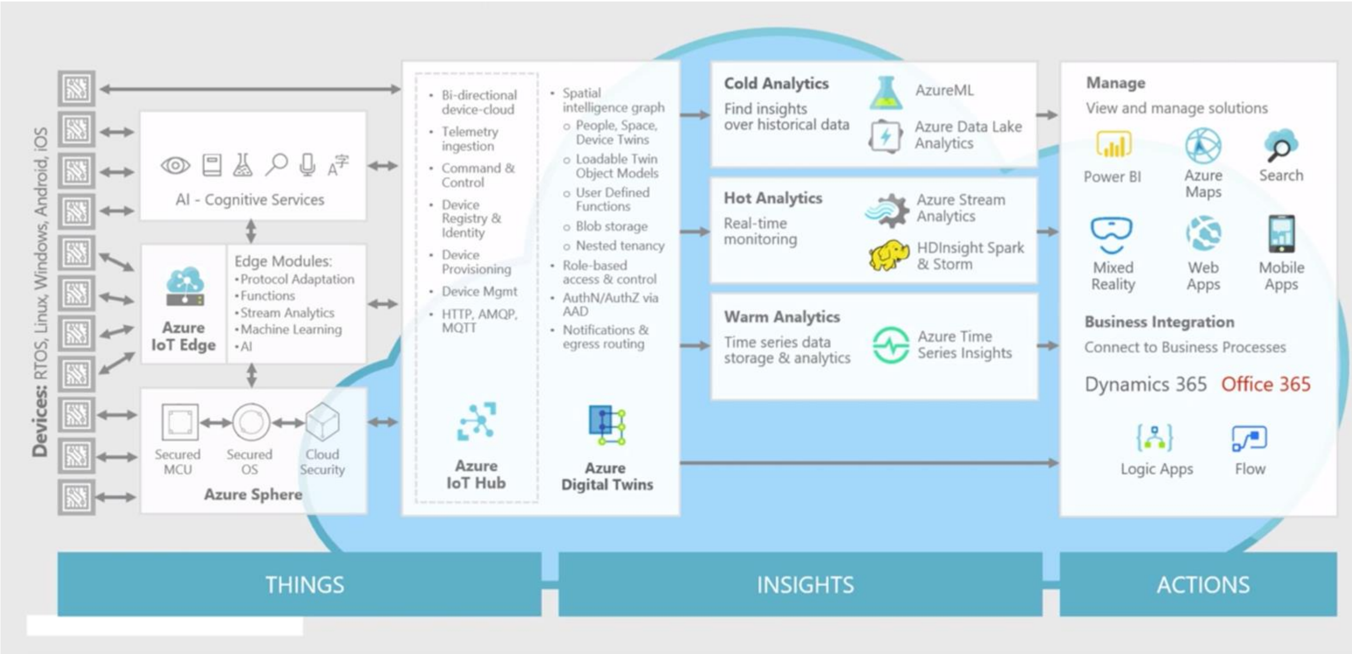


FIGURE 20 AZURE DIGITAL TWINS: MODEL AND INTERACT WITH THE REAL WORLD, WITH REFERENCE TO (JULIESETO, 2019)

As Figure 21 illustrates, the system works as follow:

- Collecting data: A specific application or code (e.g., JAVA) would be developed and employed depending on the needs and requirements.
  This application collects data from all sensors allocated in the building.

- Storing data: The application stores the collected data in the Azure Digital Twins cloud.

- Requesting data: The application query data from Azure Digital Twins by using API (Application Programming Interface).
  “API stands for Application Programming Interface. An API is a software intermediary that allows two applications to talk to each other. In other words, an API is the messenger that delivers your request to the provider that you’re requesting it from and then delivers the response back to you.”(Pearlman, 2016)

- Exchanging data: Azure Digital Twins sends the requested data to the application.

- Sending orders: The exchanged data would be analyzed, and thus the application sends commands to the linked system (e.g., ventilation system, lighting system, heating system, etc.) tells that system what should be done to be able to optimize the conditions in the building.

- Presenting data: The data can be presented using various systems, such as a 3d model running on the game engine UNITY, which provides the possibility to walk around virtually inside the building looking at real-time data at its original position.

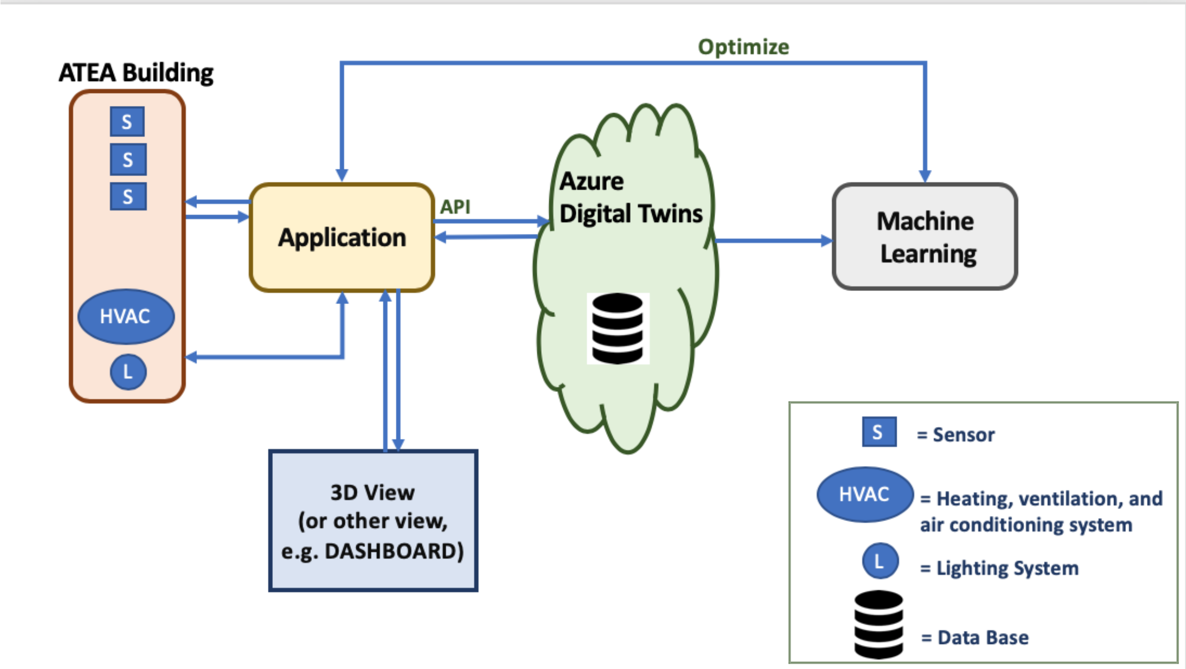


FIGURE 21 THE DIGITAL TWIN ENGINE FOR ATEA AS BUILDING

After a while, when sufficient collected data is available, machine learning would become ready to be utilized. Thus, the program would decide by itself what is the best solution and decision to take.

The application controlling the different systems would require to be manually re-written in order to make adjustments for a higher optimized outcome. However, with the machine-learning, this would be automatically provided. The machine-learning program utilizes the historical data to predict the outcome before it occurs, and therefore would be able to determine the best values to send to the application which then affects the system in an optimized way without human interaction or codes re-writings.

FIGURE 22 A PICTURE TAKEN FROM ATEA AS BUILDING DT, (ATEA, PERSONAL COMMUNICATION, APRIL 2019)

7.1. Case-study No. 1: Digital twin as risk indicator, Operation phase

First of all, this case has been developed to show how DT could be utilized throughout the operation phase as a risk indicator tool based on risk acceptance criterion. These are predefined to control CO2 levels in the building, using available historical as well as real-time data, in addition, to adjust CO2 levels to the accepted level. I.e., managing operational risk (operational risk is defined as *"the risk of loss resulting from inadequate or failed internal processes, people and systems or from external events."* (BIS, 2001, p. 2)).

Analyzing data:

The data which is shown in Table 9 in the Appendix is real-time data taken from the applied system in the building. As seen in the table it is the available data through the period of two months between the dates: 01.02.19 to 01.04.19. The data is periodically updated every 5 minutes = 300 seconds (usually there is a limit of the number of calls allowed within 24 hours for API, which could be translated in this case to a call every 5 minutes). The graph illustrates this data showed in Figure 23, where there are three lines with three different colors indicating the following:

- CO2 data: the yellow line.
- Humidity data: the red line.
- Temperature data: the blue line.

Noting that this case-study is limited to the CO2 data.

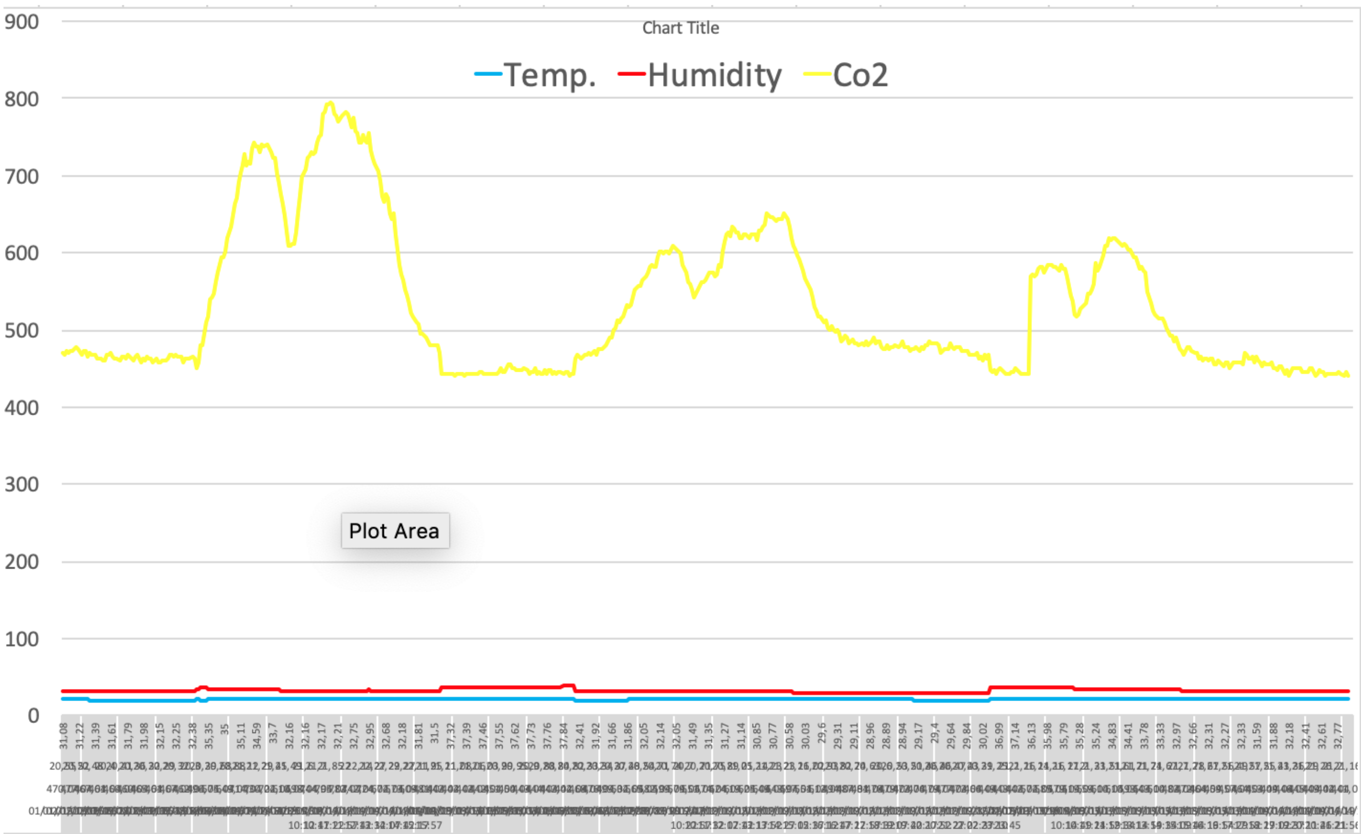


FIGURE 23 THE GRAPH SHOWING THE CO2 LEVEL, TEMPRATURE AND HUMIDITY, BASED ON REAL-TIME DATA FROM TABLE 9 IN APPENDIX.

As Figure 24 illuminates, there is a threshold for CO2 levels indoors. those levels affect the Indoor air quality (IAQ) which is defined in Wikipedia (“Indoor air quality,” 2019) as “the air quality within and around buildings and structures. IAQ is known to affect the health, comfort and well-being of building occupants. Poor indoor air quality has been linked to Sick Building Syndrome, reduced productivity and impaired learning in schools.”
IAQ is part of indoor environmental quality (IEQ), which as per Wikipedia (“Indoor air quality,” 2019) includes IAQ in addition to other different aspects (psychological and physical) of life indoors (such as acoustics, lighting, visual quality, and thermal comfort).

In other words, since this case is about an office building, this could refer to a healthy workplace environment (HWE) which is besides having a healthy physical atmosphere, companies must provide a good environment that leads to a higher productivity.

As Figure 24 and Figure 25 show, the highest indoor acceptable level for CO_2 is 1000 ppm, and the right average level for rooms indoor is 350-1000 ppm.

What are safe levels of CO and CO2 in rooms?

CO2

250-350ppm	Normal background concentration in outdoor ambient air
350-1,000ppm	Concentrations typical of occupied indoor spaces with good air exchange
1,000-2,000ppm	Complaints of drowsiness and poor air.
2,000-5,000 ppm	Headaches, sleepiness and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present.
5,000	Workplace exposure limit (as 8-hour TWA) in most jurisdictions.
>40,000 ppm	Exposure may lead to serious oxygen deprivation resulting in permanent brain damage, coma, even death.

Figure 24 Safe levels of CO2 in rooms based on ("Indoor air quality," 2019)

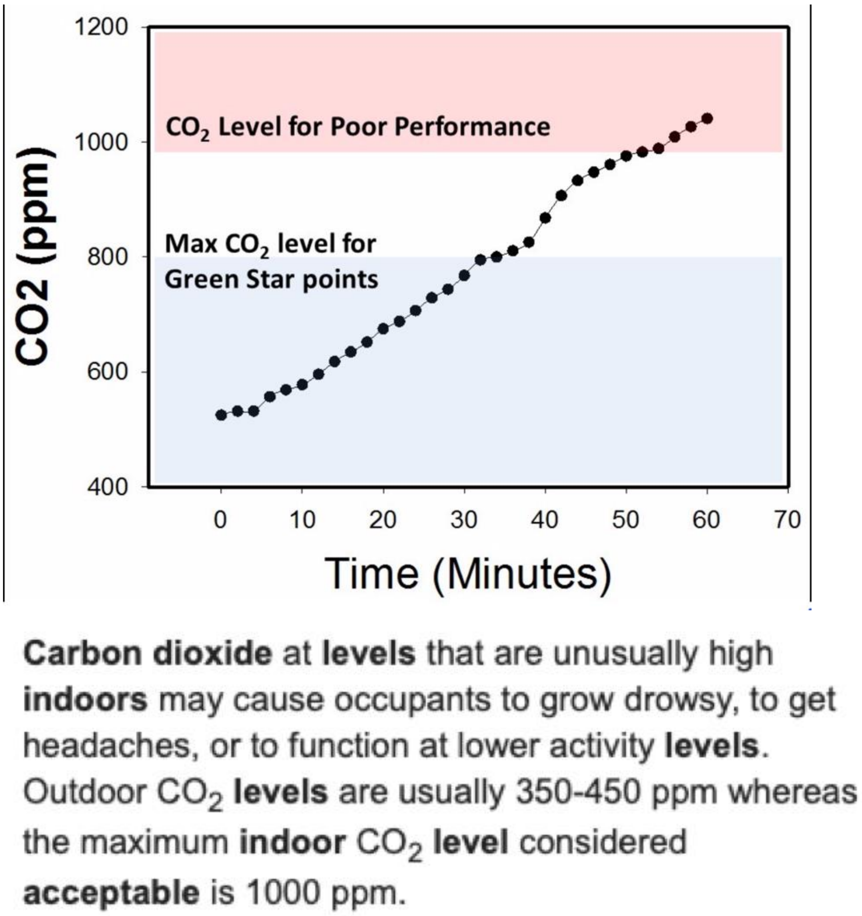


FIGURE 25 CO2 INDOOR ACCEPTABLE LEVELS WITH REFERENCE TO ("INDOOR AIR QUALITY," 2019)

Applying what has been mentioned above to the data pulled from the system, as shown in Figure 26, there are six high peaks for CO2 level (where CO2 level is between 500-800 ppm), and stabilization periods in between (where CO2 level is between 400-500 ppm).

The first two peaks where the CO2 level is close to 800 ppm, the IAQ was considered as poor quality which led to lower the performance of employees with direct effect on their alertness and health. The company had a situation with many employees having to leave the building due to dizziness, lower ability on keeping high focus and not feeling comfortable. That had a direct effect on productivity and therefore has adverse impacts on the workflow in the company in the form of health, safety and cost.

Digital twin and machine learning roles:

What is evident from the Figure 26 is the obvious role of the DT and basically the role of the machine learning. The DT has managed to apply learnings from the available historical data. This has been done by analyzing, synchronizing real-time data and dealing with repeated situations. By applying these learnings, it managed to fix such situations quickly before reaching high peaks depending on preset parameters which applied as risk acceptance criterion. This could be seen in the graph, where after having the first two peaks 1 and 2, the CO_2 level managed to be kept stable in period B. When these levels started to become high again reaching to point 3 and 4, There was a quicker response in adjusting the system. Checking the graph afterward from period C to 5 and 6 and going forward to D. This could be explained as the machine-learning program utilizes the historical data to predict the outcome before it happens and therefore, it would be able to determine the best values to send to the application which affects the system in an optimized way without human interaction or re-writing of the code.

Therefore, based on the inputs, the data and risk acceptance criterion, the system would either adjust the parameters automatically or send a command to the alarm system to be turned on, thus showing in the module alarms, in addition to report problems and send notifications if required.

This could be translated from the risk management, or to be more specific, from the enterprise risk management (ERM) perspective (ERM as per (Tarantino & Cernauskas, 2012, p. 73) "comprises the methods and processes used by organizations to manage risks and seize opportunities related to the achievement of their objectives."), as that the system in cooperation with the machine learning utilizing the historical-data to identify events, situations and the related risks. Assess those risks in terms of their likelihood and consequences, then monitor or report the risk depending on the available data as well as predefined risk acceptance criteria. Then it will take the appropriate mitigation actions which could be avoidance by stopping activity or solving the issue by reducing the likelihood or the consequences through mitigation, monitoring by ongoing tracking or accepting the risk and not taking any action if applicable.

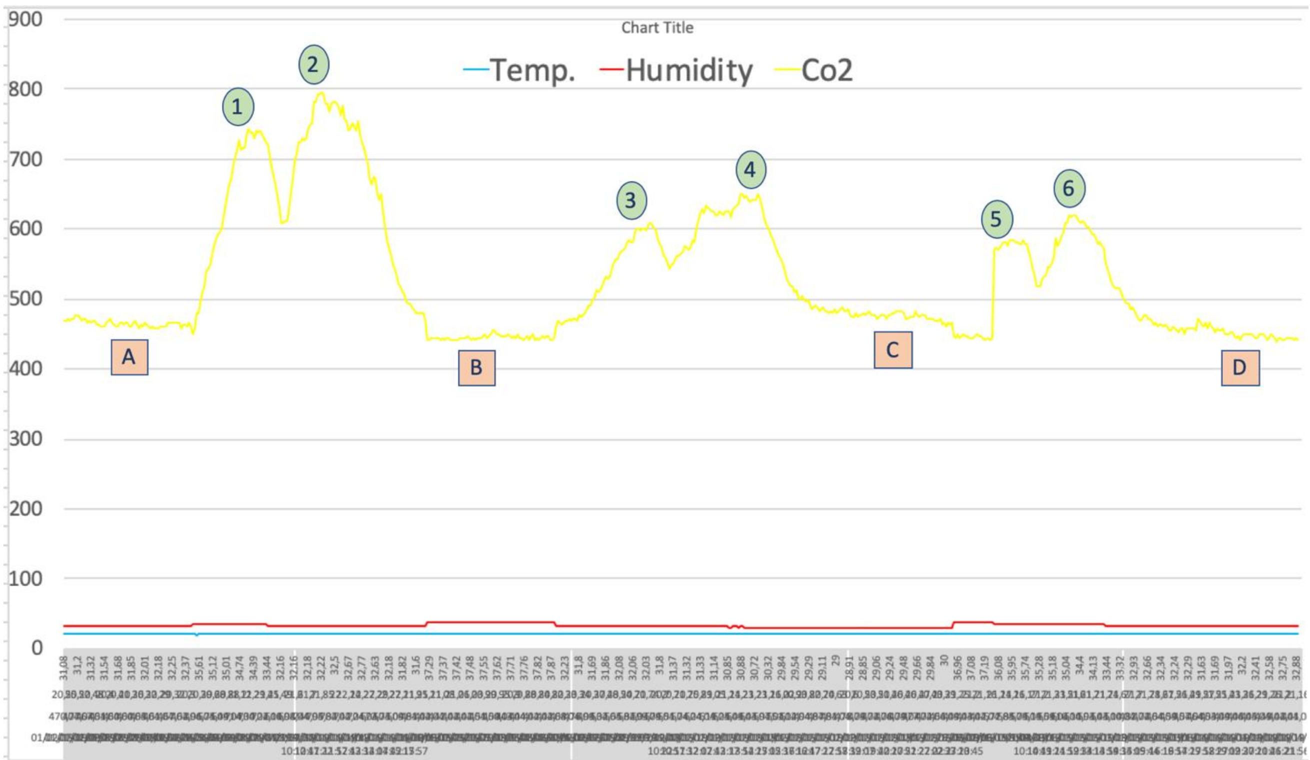


FIGURE 26 THE GRAPH SHOWING CO2 LEVEL INCLUDING PEAK POINTS AND STABILIZATION PERIODS.

Further expectations:

It is expected in this case to have lower peaks overtime keeping the CO2 level stable just as it is in periods A-B-C-D, and therefore providing good operational risk management by maintaining an appropriate working environment, based on keeping the risk indicator on and auto-adjusting mood , the CO2 level would remain within the acceptable limits.

7.2. Case-study No. 2: Digital twin to support decision-making, Operation phase

This case is also from the operation phase. By taking a simple sample of data, it aims to describe how DT can utilize historical data to build a model which could be used as the basis for future predictions of similar conditions (Similarities). I.e., when starting a risk analysis, it is crucial to start with identifying the initiating events (e.g., threats) acquired from earlier analysis which would help in decision-making by expressing the risk for part of the conditions and the background knowledge on which the analysis is built. Furthermore, to show how this could be done by combining data from different inputs.

ATEA

FIGURE 27 A PICTYRE OF THE SCREEN OUTSIDE ONE MEETING ROOM, SHOWING TEMPRATURE AND CO2 LEVEL, (ATEA, PERSONAL COMMUNICATION, MAY 2019)

Analyzing data:

The data which has been used for this study-case is real-time data for the CO2 level of a specific meeting room through the period of one week. Unfortunately, due the partial availability of the DT data of this project, the access to this data was not available yet at the time writing this thesis, thus it is not included, but the graph illustrating the data is accessible. In Figure 28, the graph illustrates the data accompanied by a booking schedule sheet from outlook for the same room, same week, showed in Table 6.
Since the analyzed data is also CO2 levels, the same acceptance levels from Figure 24 are applicable.
According to Atea AS, the booking schedule from outlook calendar should be soon replaced by an application. This application would provide real-time tracking for people inside the building by their smartphones. Therefore, the system would be updated automatically and continuously by the number of people moving around the building in addition to their movements and their locations (such as number of people attending the meeting) when combined with other collected data depending on the case it would raise the system knowledge and clarify the overall picture (better risk description) for better assistance, as well as time saving of collecting data from different resources such as the outlook calendars.

Bookings in Outlook					
	Monday 10.06.19	Tuesday 11.06.19	Wednesday 12.06.19	Thursday 13.06.19	Friday 14.06.19
07:00					
07:30					
08:00			Maintenance 1 person		
08:30		Meeting 4-5 ppl			
09:00					
09:30					
10:00					
10:30					
11:00					Meeting 5 ppl
11:30					
12:00					
12:30					
13:00			Meeting 3 ppl	Meeting 5 ppl	
13:30	Meeting 4-5 ppl				
14:00					
14:30		Meeting x ppl	Meeting 4-5 ppl		
15:00					
15:30					
16:00				Maint. 1 person	
16:30					
17:00					

TABLE 6 BOOKING SHEET FOR MEETING ROOM NO. 104, DURING WEEK NO.24

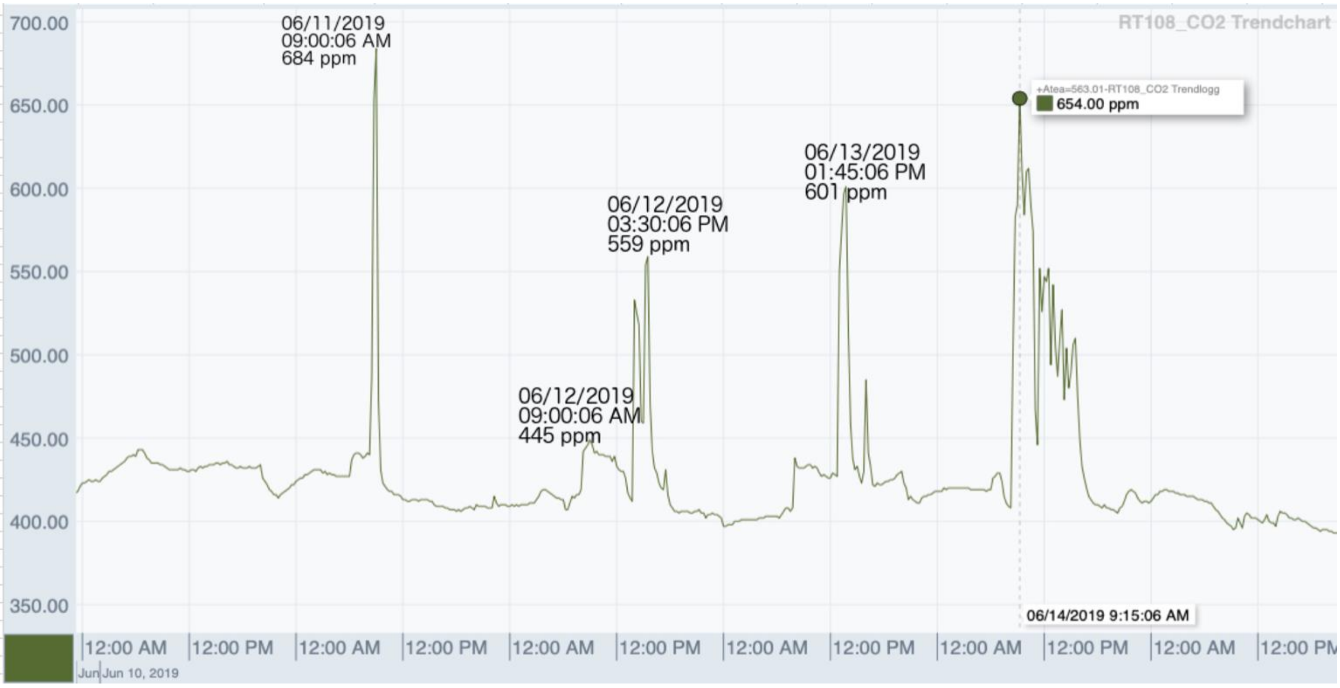


FIGURE 28 THE GRAPH SHOWING CO2 LEVEL IN MEETING ROOM NO.104 DURING WEEK NO.24

As seen from the data in Table 6 and Figure 28:

Date	Meeting time	No. of people	CO2 level	Observations	Remarks
Monday 10.06.19	13:30 – 14:00	4- 5	400 - 450 ppm/constant	___________________	Meeting was canceled
Tuesday 11.06.19	08:30 – 09:00	4- 5	684 ppm at 09:00	High CO2 level after 30 minutes	________
	14:30 – 15:00	x	400 - 450 ppm/constant	Slight effect because of short time	_________
Wednesday 12.06.19	07:00 – 10:00	1	445 ppm at 09:00	Slight effect because only 1 person	_________
	13:00 – 14:00	3	400 - 450 ppm/constant	Slight effect because of short time	_________
	14:30 – 15:00	4- 5	559 ppm at 15:30	Higher CO2 level in shorter time when having more people	_________
Thursday 13.06.19	13:00 – 14:00	5	601 ppm at 13:45	Higher CO2 level in shorter time when having more people	_________
	16:00 – 16:30	1	400 - 450 ppm/constant	Slight effect, only 1 person	_________
Friday 14.06.19	08:30 – 14:00	5	654 ppm at 09:15	High CO2 level after 45 minutes	_________

TABLE 7 ANALYZING AVAILABLE DATA

It is evident from Table 6, Figure 28 and Table 7 hat after 30 to 45 minutes of having more than one person in the room the CO2 level starts to get higher (observing that when having one person for several hours the CO2 level remains accepted and consistent). The CO2 level is in proportion to the two factors, the number of persons and the time. The more people in the room, the faster CO2 gets higher and the longer time they stay in the room, the higher the CO2 level. So, the worst-case scenario is having too many people for a long time. This gives an excellent basis to predict if a risk is presumed to exist.

Case discussion:

This sample is to show a simple example of this type of DT applications considered when performing a risk analysis, noting that the following discussion is based on (Aven, 2014, pp. 67–78).

The available data could be analyzed. A simple sample for a short period (one week) has been chosen to make it easier to be analyzed in this study-case, but in real-life case, the sample should cover more extended period in order to have useful data (e.g., for observations) as inputs when performing the analysis.

When carrying out risk analysis, the historical data as an input are being observed, estimated and used to provide information, which would be used to interpret the risk description. This description of risk would be the basic knowledge to compare different alternatives and therefore better decision-making in the next step, as well as constructing a probability model, and so forth, depending on the case. The knowledge differentiates from the decision-maker or the analyst point of view, for the decision-maker, is about understanding the risk description, whereas for the analyst it is about understanding how to understand the risk description and perform the risk assessment.

All of this provides a useful model/experience when identifying the initiating events (e.g., threats) for future analysis, studies in similar situations, which is closely related to the cause analysis, uncertainties and probabilities.

The three following essential points summarize this case:

- Information gathering: The data from Figure 28: CO2 level and Table 6: The number of people, period.
- Data and related observations: Table 7 provides a simplified example.
- Identification of scenarios: A similar booking schedule to the one from Table 6, e.g., number of attendees and period.

7.3. Case-study No. 3: Digital twin to compare alternatives, Engineering phase

This case is developed in the engineering phase which is a different phase than the two preceding cases as the studied DT was not available yet. At this phase, the company has faced a problem, which would have been avoided very easy if a DT had been implemented. The main goal of this case is to present an argument that the cost associated with constructing a DT in an early phase of the lifecycle of a project (e.g., planning or engineering) is in proportion to the usefulness of it.

Note that in this case, there is no utilized data to be analyzed.

Case description:

The case focuses on an existing problem on the first floor, storage area, as follows:
The original plan of this area is shown in Figure 29. This figure is a 3D screenshot taken from the implanted DT which shows the original plan including all the construction elements (e.g., walls and ceiling) in addition to the cabling plan and all the other internal accessories (e.g., doors and shelves).

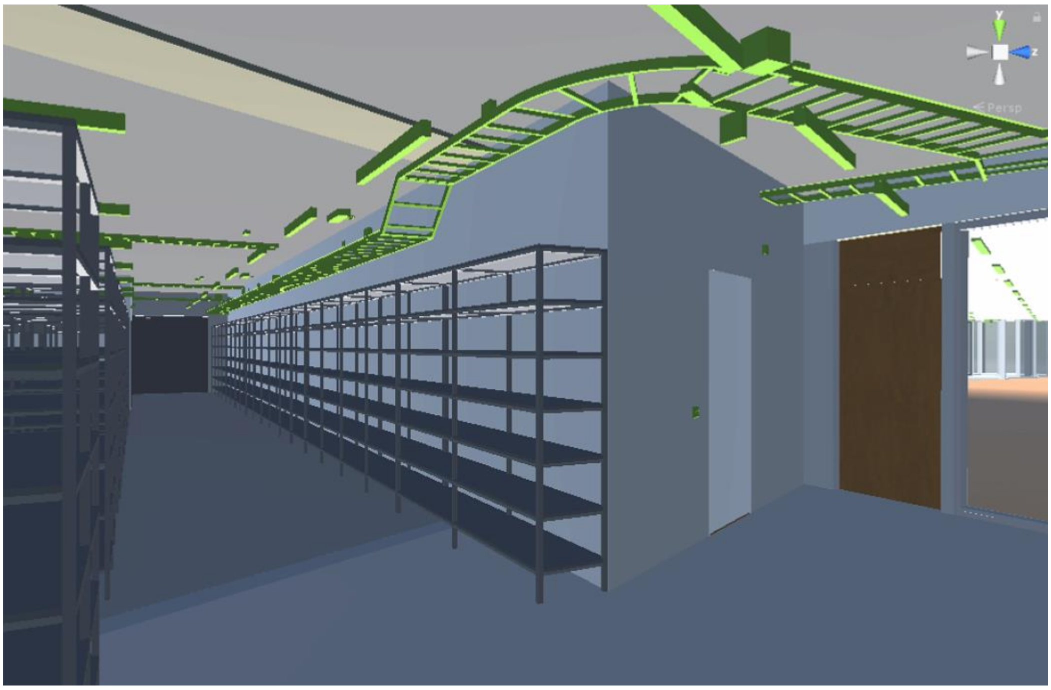


FIGURE 29 A PICTURE TAKEN FROM THE DT TO SHOW THE ORIGINAL PLAN OF THIS AREA, (ATEA, PERSONAL COMMUNICATION, JUNE 2019)

With reference to Figure 30, the existing problem mainly includes the three elements 1- 2- 3; elements 1 and 2 are reinforced concrete walls (a reinforced concrete wall is a very sensitive element, not easy to be demolished nor to any changes), element 3 is the cables rail.

As the team from Atea AS describes the case (Atea, personal communication, June 2019): During the engineering phase, traditional tools and programs have been utilized to construct the company's building. At this point there was no DT as it was not ready yet. As of finishing all the cabling and starting to build the walls, a problem was faced in the storage area as there was a collision between the two walls (number 1 and 2) with the cables trail (number 3) as seen in Figure 31 and Figure 32. This issue was not discovered by performing collision-control systems. When discovered, it was already too late to take any action. The most crucial point is that this problem has not been solved and will always exist as no flexibility is available to apply any changes in the cable plans in the future. This has many implications and serious consequences such as the high risk and extra cost that accompany solving any new problem that would occur in this area in the future. Furthermore, with this situation it is very easy to damage other cables during required maintenance.

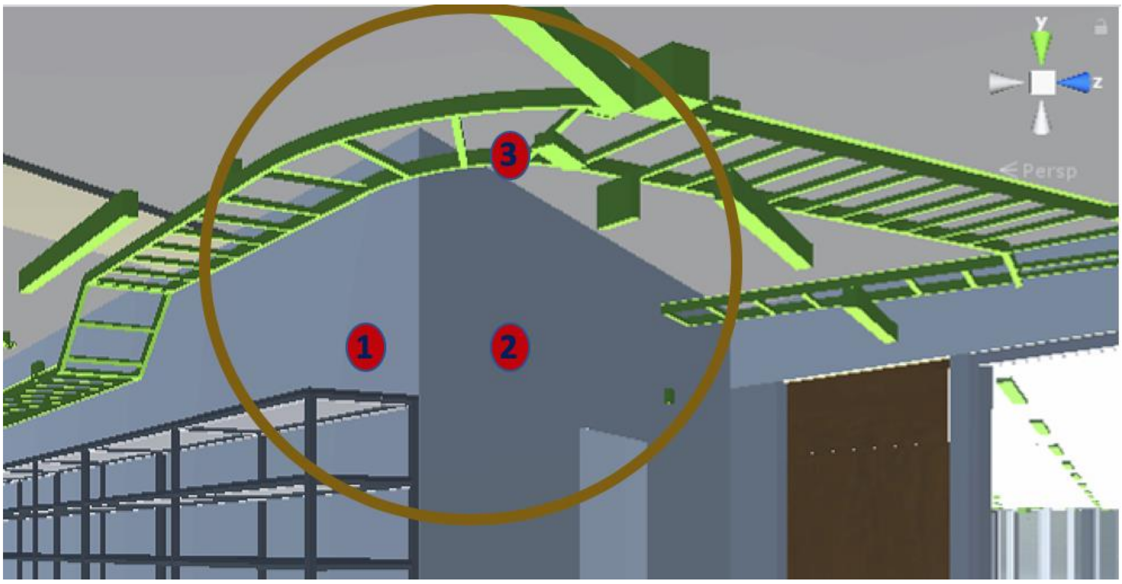


FIGURE 30 A CLOSER LOOK TO THE STUDIED AREA, (ATEA, PERSONAL COMMUNICATION, JUNE 2019)

Further discussion:

This case illuminates the importance of employing DT in such an early phase of the lifecycle of a project. It gives an example of having an unexpected failure that could be avoided very easily if DT was built and used.

FIGURE 31 A PICTURE OF THE CURRENT SITUATION (SEEN FROM ONE SIDE), (ATEA, PERSONAL COMMUNICATION, JUNE 2019)

Figure 32 A picture of the current situation (seen from another side), (Atea, personal communication, June 2019)

As seen in Figure 32, that is the current result. The problem is that the construction team did not check the dimensions on site ahead of that stage in construction as such tasks are time-consuming along with a low likelihood of occurrence. In case DT has been utilized along with a quick onsite check, the problem would be discovered instantly, or probably the DT would send a notification of having this error/failure at this area, therefore, discovering that there is an overlap between the different elements. Moreover, using augmented reality (AR) would be very useful in this case, by providing a comprehensive sight of the real current situation, including all infrastructure elements as well as construction elements. Therefore, the problem would be solved quickly in an early stage and several suggestions for new scenarios would be possible at that stage.

It would be possible during that stage to perform a risk analysis using digital twin to test different scenarios. That would definitely support taking the right decision regarding this problem, choosing between alternative solutions at that phase after establishing a risk picture in addition to compare different alternatives and solutions in terms of finding balance between different concerns such as future consequences and associated cost. It is always easier to change at an early stage where more flexibility is available for changing along with a much lower cost. Whereas, there is no point in carrying out such analysis at a later stage where the results arrive too late to affect decisions. In the operation phase, as per (Aven, 2015, p. 3,4), the decision alternatives are limited, and in this case, are even not available. It would be easier to make the required changes on paper in an earlier phase than to make changes to existing elements in a later phase.

7.4. Summary

Table 8 summarizes the main points of the three study-cases in addition to results, benefits, and highlights of each case.

	Phase	Link to Risk Analysis	Outputs and benefits	Highlights
Case-study No. 1	Operation	Risk indicator	-Self-adjustments -Alarm	Managing operational risk
Case-study No. 2	Operation	Decision-making support	-Information for the risk description	Providing experience data for future analysis
Case-study No. 3	Engineering	Comparing alternatives	-Avoiding adverse consequences -Saving cost and time	The importance of using DT in engineering phase e.g., to avoid major problem

TABLE 8 THE THREE DEVELOPED STUDY CASES

8. Discussion and Future research

This Chapter is to highlight, based on the information in Chapters 4 and 5, the limitations and challenges of digital twin technology. Also, to discuss briefly the main ideas that were presented earlier in the previous Chapters. Finally, suggestions for future research will be proposed.

8.1. Digital twin: limitations and challenges

Although digital twin technology has many benefits and advantages, it is a nascent technology and therefore it has many limitations and challenges that can be concluded based on the information in Chapters 4, 5 and 6 as follow:

- **Immature:** New technologies need some time to mature and to be trusted.

- **Lack of expertise:** New technology demands new skills, as well as new working styles and cultural norms. In other words, when the technology is nascent, it makes sense not to have enough expertise in the market. Therefore, it could be hard sometimes to get enough recourses with expertise.

- **Expensive expertise:** The shortage of required skills and experts leads to the high cost of employing them, it is a general rule of “high demand but short supply.”

- **High cost:** The total implementation cost of digital solutions may often amount to a considerable investment sum. Thus, conducting a cost-benefit analysis could be useful in order to justify the benefits obtained from incurring expenditure on such a solution.

- **Data availability:** Digital twins are, of course, data-dependent, and this could be counted as a significant limitation in cases of lack in data.

- **Model Testing:** Testing the accuracy of a model requires data that might be not available on time, and therefore, this could be a hindrance in using the model.

- **Trust:** When constructing a DT, many companies would work on providing different products and services in order to get it ready, which thus requires data sharing with digital transfer protocols. Many companies are not ready yet from an IT security point of view. Therefore, it takes longer time to build this trust.

8.2. Discussion and Recommendations

Due to higher demands for productivity, cost efficiency and optimization to be able to compete among the industrial communities in a fast-developed markets, with a shortage of academic resources and a constant focus on health and safety. It can be noticed recently that the focus on risk studies has been increasing rapidly, which can be recognized as a revolution among all industries and on different levels. On the other hand, due to the previous mentioned factors, another industrial revolution is on the raise as it is getting popular among respected industrial and academic communities, which is industry 4.0. This revolution includes a broad combination of physical and digital technologies. These two revolutions are currently allocated among the highest interest for multinational companies, industrial groups in addition to small startups. Digital twin is one of the major concepts associating the industry 4.0 revolution.

This constant search for new technologies which has the potential added value is the reason for the growing adoption and hype around digital twin. The digital twin concept is built on a history of innovations and insights. As of today, it looks like a promising concept which is receiving a lot of attention from industrial communities due to early fruitful implementations among several major companies. At the same time, there is still widespread confusion about whether to use digital twin or keep the traditional way of running businesses due to several limitations and challenges mentioned earlier in Section 8.1. Furthermore, the value added and utilization of digital twins will be different depending on the observer perspectives, demands, doubts and expectations. In other words, as Wasserman (2017) states “The Digital Twin will mean different things to different people.” This will hopefully be more clarified in the future when additional researches about this topic will emerge and more methods facilitate taking decisions regarding utilizing digital twin will be developed. Noting that, some elaborations have already started building the basis for the coming future researches.

The term risk management, as Aven (2015) describes, includes risk analysis in addition to other management elements. Risk analysis has always been open to utilize and develop new methods, tools, techniques and practices to adapt with the requirements and demands.

From Chapter 3, with reference to Aven (2015, p. 185), risk analysis is “systematic use of information and knowledge to identify sources, identify their causes and consequences and describe risk.
Risk analysis provides a basis for risk evaluation, risk treatment and risk acceptance.
Information can include historical data, theoretical analysis, informed opinions and concerns of stakeholders.”
As mentioned earlier in Chapter 3, there are two main types of risk analysis, quantitative and qualitative. Quantitative Risk Analysis is a model-based risk analysis, aims to estimate the risk in form of probability of a loss such as simulation modeling and specifically Monte Carlo simulation which has been used for decades to help when carrying out a risk analysis.

Likewise, any other used method, Monte Carlo simulation has some weaknesses and strengthen points. Due to all digital twin new additional characteristics mentioned earlier in Section 5.1, it is argued that it would probably be the new competitor of Monte Carlo simulation in the area of risk analysis. With Monte Carlo simulation, there will be always a room for human error due to the required manpower to utilize it especially when dealing with complex forms and small probabilities which can be avoided with digital twin as it is completely dependent on machine learning which will increase the trust on results and lower the associated risk value.
Digital twin might overcome Monte Carlo simulation with all its new available features.
As been explained in Chapter 5, no unified way of defining the connection or the differences between simulation modeling and digital twin has been found yet. One perspective is that the digital twin approach is the next wave in modeling, simulation and optimization technology.

Due to what has been mentioned above with all features presented currently in digital twin, beside what has been described in (Negri et al., 2017, p. 946), that the digital twin originally as a concept was born in the aerospace sector with the presence of all technologies associated to Industry 4.0, has become important and super beneficial to almost all domains including manufacturing, finance, health, energy, tech and so on. Digital twin (which must have the four core elements; model, data, uniqueness, monitor, see Section 4.4.5) based on semantic data models allows running simulations in different disciplines. This offers a static perspective by prognostic assessment at all stages of any project including the design stage, in addition to a nonstop update of the virtual representation of the object by utilizing real-time synchronization with sensed data. This representation continually reflects the system current status with a constant real-time optimizations, decision-making and predictive maintenance which provides a crystal-clear perspective regarding associated risk which leads to avoid potential losses and constantly add value. All in one product at the same time.

The comparison in Chapter 5, between digital twin and simulation modeling from both general and risk analysis approaches, explains the several new features that digital twin includes, such as user, virtual reality, real-time and mirror. Those features provide new application areas in several domains, for instance, in oil industry; real-time data is utilized while drilling offshore to enhance rapid decision-making by expertise inland. By applying digital twin and machine learning, these decisions are becoming more accurate with limited room for errors which saves well cost, improve production in addition to lower the risk. For example, in a well control situation having digital twin predictions could enhance risk analysis process by sending alarms as a result of a simulation which will lead to make the right decision and avoid a catastrophic event. In another example, applying virtual reality for offshore platforms maintenance will reduce the risk associated with manpower and human error which could be related to periodic inspections for tools, valves and so on. This will lead to minimize offshore incidents and gradually eliminate them completely. The added accuracy of risk management related to applying digital twin represents a great value to the oil industry with the constant focus on rules and regulations associated to offshore risk. As digital twin still in an early stage of developments, all of what has mentioned above is still running alongside the traditional methods as it requires to build more trust on the models generated. As a result of what is mentioned above, it is expected that the new mentioned features in digital twin would help a lot enhancing risk analysis during the life cycle of a project especially by utilizing virtual reality and real-time. I.e. combining the real-time data with simulation models from design, as well as using virtual reality, allows on the other side to produce good predictions based on the realistic data.

It has been argued that digital twin would enhance risk analysis, especially by establishing high predictions with small uncertainties using quickly generated data combined with historical data and therefore establish reasonably good predictions, accompanied by low uncertainties. Moreover, performing comparisons and evaluations as well as running simulations taking the advantage of availability of both historical and real-time data in addition to the VR and AR features. All together are available when utilizing digital twin, which would help a lot in the risk analysis process especially in the design and engineering phases where avoiding adverse consequences, significant problems and saving cost and time are easier to obtain. An excellent example to support this argument is the study-case No.3 seen in Section 7.3, where all details related to this case are shown and discussed.
One of the main concerns about building digital twin in such an early stage is that; the high cost of developing the digital twin is not in proportion with the acquired results. But that case in Section 7.3; illuminates the importance of employing digital twin and explains its benefits. On another hand, if there is a plan to build a digital twin in a later stage, then it is better to start earlier and get the most out of it in all the phases of the lifecycle of the project.
As discussed in Chapter 7, checking the other two cases from the operation phase, the obtained results, in addition to providing better understanding show two different applications of the same digital twin at the same phase. In managing operational risk, as a risk indicator tool, as well as performing self-adjustments, sending alarms and notifications and so forth. The study is particularly about maintaining healthy working environment by keeping the CO_2 within the accepted level. Another application for the digital twin is providing information which helps to build a good risk picture description and thus provides data for future analysis to help with raising the accuracy of decision-making.

Coming back to the four core elements that digital twin must-have. Ideally, digital twin supposed to provide an exact match of the processes operating the real system in real-time, but this is an exaggerated expression, as the model is an essential element of a digital twin and the notion of an exact mirror or match cannot be accessed using a model, i.e. it is just an idealization, which in all probability, will never be achieved. At the same time, this, of course, does not negate that the digital twin main idea is still the same, but it is better to express it as to provide a closer to exact match than to provide an exact match.

Digital twin would help of performing better risk analysis in a lot of cases but might not in others. This is depending on a combination of several factors and reasons that affect that;

such as the situation, phase, available resources and data, etc. It is crucial to demonstrate the need for more scientific research and development of new improved tools, techniques and practices to adapt the current risk management systems.

As it has been stated, the limitations, methodology as well and literature offered is still limited since digital twin is relatively a new concept. This is in addition to the lack of studies that link the applications of digital twin with risk analysis, as well as the need for adapting or developing new methods to perform special risk analysis and assessments. More researches in this field are expected to be commenced in the following period, many points and important ideas requires further discussions and deep analysis.

As always has been, risk management embraced new technologies and acquired the need to utilize them when possible in order to keep abreast of new developments in the society and industries, in addition to becoming more dynamic. However, this would need time to establish a good picture, solid plans and highlights about how and when to cooperate with this technology to get the better out of it in a balanced way.

Recommendations

The following are some recommendations related to the digital twin topic, inspired by the information provided throughout the prior Chapters:

- Related to cost, it would be recommended to commence a comprehensive discussion to conclude whether to construct or avoid constructing a digital twin if the desired results could be met with a more cost optimized product.
- With new fields of implementations, it would be recommended to run digital twin in parallel with the traditional models where decisions would be made based on specific experience. As digital twin is based on machine learning and inputs, it will require some time before reaching the stage of building trust with the results related to the new models.
- To understand and define the expected benefits before investing in building the digital twin, in addition, to perform cost-effectiveness analysis to guarantee a successful and profitable investment.
- To have a clear long-term as well as short-term objectives of the digital twin in order to get the most outcomes out of it.

General expectations

As per (Steenstrup & Foust, 2018, p. 3), it is expected that:
“By 2022, more than 80% of asset-intensive organizations will have implemented digital twins.

By 2020, two-thirds of asset operators will use digital twins from their component suppliers, up from one-third currently.”

8.3. Future Researches

The digital twin as a rising technology still misses having a general, consistent and good formulated definition, as well as standards and best practices clear lists.

Not enough researches are available yet regards to this technology, which make decisions related to whether to use digital twin or not are more difficult.

Moreover, there is significant lack of resources and researches linking digital twin to risk from all perspectives, both as a tool to enhance risk analysis and risk assessment processes, or to conduct a proper risk analysis for different existing digital twins from different industries, such as, a digital twin of an offshore platform, a digital twin of a manufacturing system and so forth.

According to this, a suggestion for future research is to perform a complete risk assessment for a chosen digital twin, e.g., the one used in this thesis; this would be an interesting research including all its details.

Another suggestion is to develop and design a new method with a possible name (RAMAD – Risk Assessment Method for Any Digital twin), this method could be designed and developed with the main idea to help produce an efficient risk assessment for digital twins, which can be performed simply by a random user or by risk analysis expert. There is no clear vision to describe this method, it is just an initial proposal for a basic idea needs a more profound study, but it supposed to be exciting research well worth the effort.

Many more ideas would be indeed suggested, though, the scarcity of available resources that combine digital twin and risk studies leaves the door widely open for many new and useful future proposals.

9. Conclusion

The inspiration to write this master thesis was mostly due to the general unclear picture and questions related to this topic such as; what does the term "Digital Twin" exactly mean? Is it really a new technology or it is just a re-brand of what already exists? What are the differences between digital twin and simulation modeling? Why would it be important to have a digital twin, and what additional benefits can it provide? How could a digital twin be linked to the risk concept? How could a digital twin be used to enhance risk analysis?
Also, still, many other ideas and questions remain to be put forward.

The crucial question in this research is:
From a risk analysis perspective; how would digital twin technology differentiates itself from simulation modeling, and how it can be utilized to carry out an improved and accurate risk analysis?

The digital twin is a nascent concept, simulation is a key aspect related to this concept. The best way to link the two concepts together is, as Rosen et al. (2015) explain, that simulation is an essential functionality in the digital twin concept. However, digital twin extends simulation augmenting it with real-time data and improving its fidelity. I.e., digital twin excels simulation with many new features as been illustrated in Section 5.1, such as user, virtual reality, real-time, and mirror. Those features also provide new application areas; for instance, a monitor tool builds on real-time data and improved maintenance. It is expected that these new features, in addition to their applications, would help a lot enhancing risk analysis during the life cycle of a project, especially using virtual reality and real-time updates. I.e., combining the real-time data with simulation models from design, as well as using virtual reality, allows on the other side to produce good predictions based on the realistic data. DT helps to improve situational awareness as well as empower better responses to changing conditions; thus, this would lead to take better decisions regarding maintenance when performing risk analysis. Digital Twin could be very beneficial in the operation phase to manage operational risk throughout the whole phase, or to aid in supporting decision-making by providing more rugged data for future analysis. Whereas, in the design phase, digital twin could have an essential role helping in alternatives comparisons. Also, avoiding adverse consequences as well as saving cost and time, in the construction phase.
Utilizing this technology is still in its infancy stage and many more applications and benefits to be discovered in the soon future.

On another side, digital twin as any other technology has many limitations and challenges that could be faced, such as the high cost related to construction and acquiring the right expertise, which is rare at the same time, data availability and so forth. Using digital twin during the life cycle of any project would be accompanied with many threats and opportunities at the same time. This relates to many factors such as the type of the project, the phase, the circumstances, etc.

In recent years, risk management achieved great success by showing an important role among different industries and domains, as well as by embracing new technologies. There has been an increased focus on it as there is a strong belief that risk management could provide a proper tool for balancing the conflicts inherent in exploring opportunities in one hand and avoiding losses, accidents and disasters in the other hand. Different standards and frameworks have been developed to identify, assess and manage risk effectively. So, with the rapid development in technology, it is necessary to get the advantage of these new technologies to enhance risk management and risk analysis, as well as to improve risk assessment methods in order to follow the rapid growth and development involved. Digital twin requires more research to be performed in order to enhance its usage in the areas of risk management in general and risk analysis in particular. Looking at the current situation and what is in the horizon, it is very clear that digital twin will be a major part of risk management future.

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Appendix – Data for Case-study NO. 1

The data shown in Table 9 is the real-time data used in Case-study No. 1:

Date	Co2	T	H	Date	Co2	T	H
01/02/19 0:23	470,04	20,55	31,08	01/02/19 2:53	465,04	20,4	31,73
01/02/19 0:28	469,04	20,55	31,09	01/02/19 2:58	464,04	20,39	31,76
01/02/19 0:33	472,04	20,55	31,11	01/02/19 3:03	467,04	20,38	31,79
01/02/19 0:38	470,04	20,54	31,13	01/02/19 3:08	465,04	20,37	31,81
01/02/19 0:43	472,04	20,53	31,15	01/02/19 3:13	462,04	20,37	31,83
01/02/19 0:48	472,04	20,53	31,16	01/02/19 3:18	460,04	20,36	31,85
01/02/19 0:53	476,04	20,53	31,18	01/02/19 3:23	466,04	20,35	31,89
01/02/19 0:58	477,04	20,52	31,2	01/02/19 3:28	468,04	20,35	31,9
01/02/19 1:03	474,04	20,51	31,22	01/02/19 3:33	463,04	20,35	31,92
01/02/19 1:08	469,04	20,51	31,23	01/02/19 3:38	458,04	20,34	31,95
01/02/19 1:13	473,04	20,5	31,26	01/02/19 3:43	464,04	20,33	31,98
01/02/19 1:18	473,04	20,49	31,28	01/02/19 3:48	461,04	20,32	32
01/02/19 1:23	465,04	20,49	31,29	01/02/19 3:53	465,04	20,32	32,01
01/02/19 1:28	470,04	20,48	31,32	01/02/19 3:58	463,04	20,32	32,04
01/02/19 1:33	467,04	20,48	31,32	01/02/19 4:03	462,04	20,32	32,06
01/02/19 1:38	469,04	20,47	31,35	01/02/19 4:08	457,04	20,31	32,08
01/02/19 1:43	468,04	20,45	31,39	01/02/19 4:13	462,04	20,31	32,1
01/02/19 1:48	463,04	20,44	31,42	01/02/19 4:18	458,04	20,3	32,11
01/02/19 1:53	463,04	20,44	31,44	01/02/19 4:23	459,04	20,29	32,15
01/02/19 1:58	462,04	20,43	31,48	01/02/19 4:28	461,04	20,29	32,18
01/02/19 2:03	461,04	20,42	31,5	01/02/19 4:33	461,04	20,28	32,2
01/02/19 2:08	461,04	20,4	31,54	01/02/19 4:38	461,04	20,28	32,21
01/02/19 2:13	467,04	20,39	31,57	01/02/19 4:43	462,04	20,27	32,23
01/02/19 2:18	469,04	20,39	31,59	01/02/19 4:48	467,04	20,27	32,25
01/02/19 2:23	471,04	20,4	31,61	01/02/19 4:53	467,04	20,29	32,26
01/02/19 2:28	466,04	20,4	31,63	01/02/19 4:58	466,04	20,31	32,26
01/02/19 2:33	464,04	20,4	31,65	01/02/19 5:03	467,04	20,32	32,25
01/02/19 2:38	462,04	20,41	31,67	01/02/19 5:08	465,04	20,32	32,28
01/02/19 2:43	460,04	20,41	31,68	01/02/19 5:13	465,04	20,32	32,29
01/02/19 2:48	465,04	20,41	31,71	01/02/19 5:18	465,04	20,32	32,31

01/02/19 5:23	459,04	20,31	32,31	01/02/19 8:17	744,04	21,22	34,84
01/02/19 5:28	464,04	20,3	32,33	01/02/19 8:22	737,04	21,25	34,59
01/02/19 5:33	464,04	20,3	32,36	01/02/19 8:27	737,04	21,27	34,55
01/02/19 5:38	462,04	20,3	32,37	01/02/19 8:32	730,04	21,29	34,39
01/02/19 5:43	465,04	20,3	32,38	01/02/19 8:37	740,04	21,33	34,4
01/02/19 5:48	462,04	20,3	32,39	01/02/19 8:42	739,04	21,36	34,25
01/02/19 5:53	451,04	20,93	33,69	01/02/19 8:47	740,04	21,39	34,1
01/02/19 5:58	457,04	20,95	33,71	01/02/19 8:52	735,04	21,41	33,92
01/02/19 6:03	479,04	20,23	36,12	01/02/19 8:57	731,04	21,42	33,87
01/02/19 6:07	480,04	20,31	35,84	01/02/19 9:02	724,04	21,44	33,7
01/02/19 6:12	496,04	20,39	35,61	01/02/19 9:07	722,04	21,45	33,44
01/02/19 6:17	509,04	20,47	35,53	01/02/19 9:12	704,04	21,45	33,32
01/02/19 6:22	518,04	20,53	35,35	01/02/19 9:17	690,04	21,45	33,11
01/02/19 6:27	539,04	20,58	35,25	01/02/19 9:22	676,04	21,45	32,88
01/02/19 6:32	543,04	20,62	35,22	01/02/19 9:27	664,04	21,46	32,74
01/02/19 6:37	548,04	20,65	35,15	01/02/19 9:32	648,04	21,46	32,58
01/02/19 6:42	563,04	20,66	35,1	01/02/19 9:37	630,04	21,46	32,39
01/02/19 6:47	575,04	20,68	35,12	01/02/19 9:42	610,04	21,49	32,16
01/02/19 6:52	585,04	20,72	35,13	01/02/19 9:47	609,04	21,5	32,08
01/02/19 6:57	593,04	20,76	35,07	01/02/19 9:52	612,04	21,5	31,98
01/02/19 7:02	594,04	20,78	35	01/02/19 9:57	612,04	21,51	32,13
01/02/19 7:07	602,04	20,8	34,97	01/02/19 10:02	627,04	21,53	32,09
01/02/19 7:12	618,04	20,83	35,14	01/02/19 10:07	650,04	21,55	32,02
01/02/19 7:17	633,04	20,85	35,08	01/02/19 10:12	673,04	21,57	32,27
01/02/19 7:22	649,04	20,88	35,01	01/02/19 10:17	698,04	21,6	32,16
01/02/19 7:27	663,04	20,9	35,04	01/02/19 10:22	708,04	21,62	32,16
01/02/19 7:32	672,04	20,93	35,13	01/02/19 10:27	724,04	21,63	32,23
01/02/19 7:37	691,04	20,97	35,11	01/02/19 10:32	725,04	21,64	32,21
01/02/19 7:42	703,04	21,01	35,11	01/02/19 10:37	730,04	21,66	32,24
01/02/19 7:47	712,04	21,06	35,05	01/02/19 10:42	728,04	21,68	32,07
01/02/19 7:52	727,04	21,09	35,03	01/02/19 10:47	730,04	21,69	32,14
01/02/19 7:57	714,04	21,12	34,74	01/02/19 10:52	744,04	21,7	32,18
01/02/19 8:02	717,04	21,15	34,71	01/02/19 10:57	750,04	21,72	32,19
01/02/19 8:07	716,04	21,17	34,72	01/02/19 11:02	753,04	21,74	32,17
01/02/19 8:12	736,04	21,18	34,87	01/02/19 11:07	781,04	21,76	32,29

01/02/19 11:12	783,04	21,79	32,32	01/02/19 14:07	623,04	22,31	32,41
01/02/19 11:17	793,04	21,81	32,34	01/02/19 14:12	603,04	22,3	32,29
01/02/19 11:22	793,04	21,83	32,26	01/02/19 14:17	583,04	22,29	32,23
01/02/19 11:27	795,04	21,85	32,22	01/02/19 14:22	573,04	22,27	32,18
01/02/19 11:32	792,04	21,87	32,19	01/02/19 14:27	564,04	22,26	32,13
01/02/19 11:37	780,04	21,89	32,13	01/02/19 14:32	551,04	22,23	32,06
01/02/19 11:42	778,04	21,89	32,21	01/02/19 14:37	544,04	22,21	32,02
01/02/19 11:47	769,04	21,89	32,23	01/02/19 14:42	535,04	22,19	31,97
01/02/19 11:52	778,04	21,92	32,4	01/02/19 14:47	522,04	22,17	31,9
01/02/19 11:57	781,04	21,97	32,4	01/02/19 14:52	518,04	22,14	31,87
01/02/19 12:02	782,04	22	32,5	01/02/19 14:57	509,04	22,11	31,82
01/02/19 12:07	779,04	22,05	32,49	01/02/19 15:02	508,04	22,08	31,81
01/02/19 12:12	773,04	22,05	32,56	01/02/19 15:07	496,04	22,06	31,8
01/02/19 12:17	762,04	22,08	32,66	01/02/19 15:12	495,04	22,03	31,77
01/02/19 12:22	776,04	22,1	32,75	01/02/19 15:17	493,04	22,02	31,75
01/02/19 12:27	757,04	22,11	32,72	01/02/19 15:22	489,04	21,99	31,7
01/02/19 12:32	755,04	22,13	32,74	01/02/19 15:27	486,04	21,96	31,65
01/02/19 12:37	742,04	22,14	32,67	01/02/19 15:32	481,04	21,95	31,6
01/02/19 12:42	744,04	22,15	32,7	01/02/19 15:37	480,04	21,94	31,54
01/02/19 12:47	752,04	22,16	32,83	01/02/19 15:42	480,04	21,92	31,5
01/02/19 12:52	745,04	22,16	32,78	01/02/19 15:47	480,04	21,9	31,47
01/02/19 12:57	742,04	22,18	32,78	01/02/19 15:52	481,04	21,88	31,45
01/02/19 13:02	755,04	22,23	32,95	01/02/19 15:57	470,04	21,84	31,41
01/02/19 13:07	734,04	22,27	32,8	01/02/19 16:02	442,04	21,12	37,27
01/02/19 13:12	724,04	22,27	32,77	01/02/19 16:07	442,04	21,11	37,29
01/02/19 13:17	715,04	22,27	32,73	01/02/19 16:12	444,04	21,11	37,3
01/02/19 13:22	705,04	22,27	32,71	01/02/19 16:17	443,04	21,1	37,31
01/02/19 13:27	694,04	22,29	32,69	01/02/19 16:22	443,04	21,09	37,32
01/02/19 13:32	673,04	22,28	32,55	01/02/19 16:27	443,04	21,09	37,34
01/02/19 13:37	665,04	22,27	32,58	01/02/19 16:32	441,04	21,08	37,35
01/02/19 13:42	675,04	22,28	32,68	01/02/19 16:37	443,04	21,06	37,37
01/02/19 13:47	672,04	22,29	32,63	01/02/19 16:42	442,04	21,08	37,37
01/02/19 13:52	651,04	22,29	32,5	01/02/19 16:47	443,04	21,08	37,37
01/02/19 13:57	643,04	22,3	32,49	01/02/19 16:52	444,04	21,08	37,38
01/02/19 14:02	651,04	22,31	32,59	01/02/19 16:57	441,04	21,08	37,38

01/02/19 17:02	442,04	21,08	37,39	01/02/19 19:57	444,04	20,86	37,77
01/02/19 17:07	442,04	21,07	37,39	01/02/19 20:02	445,04	20,88	37,75
01/02/19 17:12	442,04	21,07	37,4	01/02/19 20:07	442,04	20,88	37,76
01/02/19 17:17	442,04	21,06	37,42	01/02/19 20:12	444,04	20,88	37,76
01/02/19 17:22	444,04	21,06	37,43	01/02/19 20:17	447,04	20,88	37,76
01/02/19 17:27	443,04	21,06	37,43	01/02/19 20:22	442,04	20,88	37,76
01/02/19 17:32	443,04	21,05	37,44	01/02/19 20:27	447,04	20,88	37,76
01/02/19 17:37	445,04	21,05	37,45	01/02/19 20:32	449,04	20,88	37,77
01/02/19 17:42	446,04	21,04	37,46	01/02/19 20:37	442,04	20,86	37,78
01/02/19 17:47	444,04	21,03	37,46	01/02/19 20:42	445,04	20,85	37,8
01/02/19 17:52	442,04	21,03	37,48	01/02/19 20:47	442,04	20,84	37,82
01/02/19 17:57	444,04	21,02	37,49	01/02/19 20:52	445,04	20,83	37,83
01/02/19 18:02	442,04	21,02	37,5	01/02/19 20:57	446,04	20,83	37,83
01/02/19 18:07	444,04	21,02	37,5	01/02/19 21:02	443,04	20,83	37,84
01/02/19 18:12	444,04	21,01	37,52	01/02/19 21:07	446,04	20,83	37,84
01/02/19 18:17	443,04	21	37,53	01/02/19 21:12	446,04	20,83	37,85
01/02/19 18:22	446,04	21	37,55	01/02/19 21:17	441,04	20,82	37,87
01/02/19 18:27	451,04	20,99	37,55	01/02/19 21:22	442,04	20,82	37,87
01/02/19 18:32	445,04	20,99	37,56	01/02/19 21:27	443,04	20,82	37,88
01/02/19 18:37	446,04	20,98	37,57	01/02/19 21:32	462,04	20,29	32,41
01/02/19 18:42	450,04	20,97	37,58	01/02/19 21:37	469,04	20,3	32,42
01/02/19 18:47	455,04	20,97	37,59	01/02/19 21:42	465,04	20,32	32,41
01/02/19 18:52	456,04	20,96	37,6	01/02/19 21:47	464,04	20,33	32,4
01/02/19 18:57	451,04	20,96	37,61	01/02/19 21:52	465,04	20,33	32,28
01/02/19 19:02	450,04	20,95	37,62	01/02/19 21:57	468,04	20,33	32,23
01/02/19 19:07	448,04	20,95	37,63	01/02/19 22:02	469,04	20,33	32,11
01/02/19 19:12	448,04	20,94	37,64	01/02/19 22:07	471,04	20,33	32,07
01/02/19 19:17	448,04	20,93	37,65	01/02/19 22:12	469,04	20,34	32,02
01/02/19 19:22	448,04	20,93	37,66	01/02/19 22:17	471,04	20,33	31,98
01/02/19 19:27	451,04	20,91	37,69	01/02/19 22:22	473,04	20,33	31,92
01/02/19 19:32	448,04	20,91	37,69	01/02/19 22:27	469,04	20,34	31,9
01/02/19 19:37	443,04	20,9	37,71	01/02/19 22:32	476,04	20,34	31,8
01/02/19 19:42	446,04	20,89	37,73	01/02/19 22:37	474,04	20,34	31,77
01/02/19 19:47	445,04	20,88	37,74	01/02/19 22:42	478,04	20,36	31,72
01/02/19 19:52	450,04	20,86	37,76	01/02/19 22:47	480,04	20,38	31,71

01/02/19 22:52	485,04	20,39	31,67	01/03/19 1:45	602,04	20,72	31,98
01/02/19 22:57	491,04	20,37	31,64	01/03/19 1:50	598,04	20,72	31,94
28/02/19 23:00	491,04	20,37	31,66	01/03/19 1:55	585,04	20,71	31,87
28/02/19 23:05	499,04	20,37	31,69	01/03/19 2:00	579,04	20,7	31,8
28/02/19 23:10	502,04	20,38	31,73	01/03/19 2:05	574,04	20,68	31,73
28/02/19 23:15	513,04	20,4	31,75	01/03/19 2:10	563,04	20,69	31,63
28/02/19 23:20	511,04	20,42	31,78	01/03/19 2:15	559,04	20,7	31,54
28/02/19 23:25	514,04	20,44	31,78	01/03/19 2:20	552,04	20,71	31,49
28/02/19 23:30	517,04	20,45	31,82	01/03/19 2:25	543,04	20,71	31,47
28/02/19 23:35	526,04	20,47	31,89	01/03/19 2:30	548,04	20,7	31,41
28/02/19 23:40	532,04	20,48	31,86	01/03/19 2:35	551,04	20,71	31,37
28/02/19 23:45	529,04	20,49	31,85	01/03/19 2:40	556,04	20,72	31,38
28/02/19 23:50	533,04	20,5	31,95	01/03/19 2:45	563,04	20,72	31,4
28/02/19 23:55	542,04	20,5	32	01/03/19 2:50	562,04	20,72	31,36
01/03/19 0:00	551,04	20,5	32,01	01/03/19 2:55	564,04	20,71	31,4
01/03/19 0:05	558,04	20,52	32,06	01/03/19 3:00	569,04	20,72	31,35
01/03/19 0:10	556,04	20,53	32,06	01/03/19 3:05	575,04	20,72	31,37
01/03/19 0:15	565,04	20,54	32,08	01/03/19 3:10	574,04	20,75	31,32
01/03/19 0:20	568,04	20,56	32,05	01/03/19 3:15	570,04	20,76	31,26
01/03/19 0:25	570,04	20,61	32,1	01/03/19 3:20	573,04	20,77	31,23
01/03/19 0:30	574,04	20,63	32,1	01/03/19 3:25	584,04	20,78	31,23
01/03/19 0:35	581,04	20,66	32,1	01/03/19 3:30	582,04	20,81	31,11
01/03/19 0:40	585,04	20,68	32,1	01/03/19 3:35	601,04	20,84	31,24
01/03/19 0:45	582,04	20,7	32,06	01/03/19 3:40	613,04	20,86	31,27
01/03/19 0:50	582,04	20,71	32,06	01/03/19 3:45	624,04	20,89	31,33
01/03/19 0:55	594,04	20,73	32,1	01/03/19 3:50	627,04	20,9	31,39
01/03/19 1:00	602,04	20,74	32,14	01/03/19 3:55	622,04	20,93	31,27
01/03/19 1:05	601,04	20,74	32,07	01/03/19 4:00	633,04	20,96	31,3
01/03/19 1:10	598,04	20,74	32,03	01/03/19 4:05	631,04	20,98	31,27
01/03/19 1:15	602,04	20,74	32,06	01/03/19 4:10	626,04	21	31,15
01/03/19 1:20	601,04	20,74	32,05	01/03/19 4:15	626,04	21,03	31,18
01/03/19 1:25	599,04	20,74	32,03	01/03/19 4:20	619,04	21,05	31,14
01/03/19 1:30	605,04	20,72	32,07	01/03/19 4:25	619,04	21,06	31,07
01/03/19 1:35	609,04	20,73	32,08	01/03/19 4:30	625,04	21,08	31,07
01/03/19 1:40	605,04	20,73	32,05	01/03/19 4:35	624,04	21,1	31,03

01/03/19 4:40	619,04	21,11	30,99	01/03/19 7:35	518,04	20,94	29,66
01/03/19 4:45	625,04	21,12	30,96	01/03/19 7:40	518,04	20,92	29,6
01/03/19 4:50	625,04	21,13	30,91	01/03/19 7:45	510,04	20,94	29,57
01/03/19 4:55	625,04	21,14	30,85	01/03/19 7:50	512,04	20,93	29,54
01/03/19 5:00	616,04	21,16	30,85	01/03/19 8:00	502,04	20,92	29,43
01/03/19 5:05	629,04	21,18	30,88	01/03/19 8:05	499,04	20,91	29,45
01/03/19 5:10	630,04	21,19	30,89	01/03/19 8:10	504,04	20,9	29,41
01/03/19 5:15	635,04	21,2	30,88	01/03/19 8:15	499,04	20,88	29,36
01/03/19 5:20	636,04	21,21	30,81	01/03/19 8:20	497,04	20,86	29,32
01/03/19 5:25	651,04	21,22	30,88	01/03/19 8:25	499,04	20,84	29,31
01/03/19 5:30	649,04	21,23	30,88	01/03/19 8:30	494,04	20,82	29,29
01/03/19 5:35	646,04	21,24	30,81	01/03/19 8:39	486,04	20,79	29,26
01/03/19 5:40	647,04	21,24	30,77	01/03/19 8:44	487,04	20,8	29,22
01/03/19 5:45	643,04	21,22	30,71	01/03/19 8:49	492,04	20,79	29,19
01/03/19 5:50	640,04	21,2	30,75	01/03/19 8:54	489,04	20,78	29,19
01/03/19 5:55	643,04	21,21	30,76	01/03/19 8:59	483,04	20,77	29,15
01/03/19 6:00	643,04	21,22	30,72	01/03/19 9:04	486,04	20,76	29,14
01/03/19 6:05	643,04	21,23	30,72	01/03/19 9:09	487,04	20,74	29,11
01/03/19 6:10	651,04	21,24	30,75	01/03/19 9:14	482,04	20,72	29,1
01/03/19 6:15	644,04	21,25	30,69	01/03/19 9:19	483,04	20,7	29,09
01/03/19 6:20	634,04	21,25	30,58	01/03/19 9:24	481,04	20,69	29,08
01/03/19 6:25	619,04	21,25	30,46	01/03/19 9:29	482,04	20,68	29,05
01/03/19 6:30	610,04	21,23	30,4	01/03/19 9:34	480,04	20,66	29,03
01/03/19 6:35	604,04	21,2	30,36	01/03/19 9:39	486,04	20,64	29,02
01/03/19 6:40	597,04	21,16	30,32	01/03/19 9:44	481,04	20,63	29
01/03/19 6:45	591,04	21,14	30,27	01/03/19 9:49	483,04	20,66	28,96
01/03/19 6:50	585,04	21,11	30,22	01/03/19 9:54	485,04	20,66	28,93
01/03/19 6:55	577,04	21,09	30,12	01/03/19 9:59	489,04	20,66	28,91
01/03/19 7:00	568,04	21,09	30,03	01/03/19 10:04	482,04	20,65	28,91
01/03/19 7:05	561,04	21,07	29,95	01/03/19 10:09	484,04	20,64	28,92
01/03/19 7:10	558,04	21,04	29,93	01/03/19 10:14	485,04	20,62	28,91
01/03/19 7:15	551,04	21,02	29,84	01/03/19 10:19	478,04	20,6	28,91
01/03/19 7:20	541,04	21,01	29,79	01/03/19 10:24	474,04	20,59	28,9
01/03/19 7:25	529,04	20,98	29,75	01/03/19 10:29	474,04	20,57	28,89
01/03/19 7:30	524,04	20,96	29,72	01/03/19 10:34	479,04	20,55	28,88

01/03/19 10:39	475,04	20,54	28,87	01/03/19 13:44	477,04	20,45	29,76
01/03/19 10:44	478,04	20,52	28,87	01/03/19 13:54	473,04	20,44	29,79
01/03/19 10:49	477,04	20,52	28,85	01/03/19 13:59	472,04	20,44	29,82
01/03/19 10:54	479,04	20,53	28,85	01/03/19 14:04	472,04	20,43	29,84
01/03/19 10:59	477,04	20,53	28,92	01/03/19 14:09	473,04	20,43	29,87
01/03/19 11:04	480,04	20,53	28,92	01/03/19 14:14	468,04	20,42	29,88
01/03/19 11:09	484,04	20,53	28,94	01/03/19 14:19	468,04	20,42	29,91
01/03/19 11:14	477,04	20,53	29,01	01/03/19 14:24	469,04	20,41	29,93
01/03/19 11:19	478,04	20,53	29,06	01/03/19 14:29	471,04	20,4	29,95
01/03/19 11:24	477,04	20,52	29,06	01/03/19 14:34	463,04	20,39	29,98
01/03/19 11:29	472,04	20,51	29,06	01/03/19 14:39	466,04	20,39	30
01/03/19 11:34	475,04	20,49	29,07	01/03/19 14:44	461,04	20,39	30,02
01/03/19 11:39	476,04	20,48	29,09	01/03/19 14:49	467,04	20,39	30,05
01/03/19 11:44	478,04	20,47	29,14	01/03/19 14:54	464,04	20,37	30,07
01/03/19 11:49	476,04	20,46	29,17	01/03/19 14:59	467,04	20,36	30,09
01/03/19 11:54	472,04	20,45	29,22	01/03/19 15:04	447,04	21,27	36,93
01/03/19 11:59	477,04	20,44	29,22	01/03/19 15:09	445,04	21,26	36,95
01/03/19 12:04	476,04	20,46	29,24	01/03/19 15:14	449,04	21,25	36,96
01/03/19 12:09	480,04	20,47	29,27	01/03/19 15:19	444,04	21,25	36,98
01/03/19 12:14	479,04	20,47	29,3	01/03/19 15:24	448,04	21,24	36,99
01/03/19 12:19	484,04	20,47	29,32	01/03/19 15:29	450,04	21,23	37,01
01/03/19 12:24	483,04	20,46	29,35	01/03/19 15:34	447,04	21,22	37,03
01/03/19 12:29	482,04	20,46	29,4	01/03/19 15:39	446,04	21,22	37,05
01/03/19 12:34	483,04	20,46	29,45	01/03/19 15:44	444,04	21,21	37,07
01/03/19 12:39	479,04	20,46	29,48	01/03/19 15:49	443,04	21,2	37,08
01/03/19 12:44	471,04	20,45	29,51	01/03/19 15:54	445,04	21,19	37,1
01/03/19 12:49	473,04	20,46	29,56	01/03/19 15:59	446,04	21,18	37,12
01/03/19 12:59	475,04	20,46	29,56	01/03/19 16:04	450,04	21,18	37,14
01/03/19 13:04	474,04	20,47	29,57	01/03/19 16:09	448,04	21,17	37,16
01/03/19 13:09	474,04	20,47	29,61	01/03/19 16:14	446,04	21,17	37,17
01/03/19 13:14	483,04	20,47	29,64	01/03/19 16:19	443,04	21,16	37,18
01/03/19 13:24	477,04	20,47	29,66	01/03/19 16:24	442,04	21,16	37,19
01/03/19 13:29	475,04	20,47	29,69	01/03/19 16:29	443,04	21,15	37,2
01/03/19 13:34	477,04	20,46	29,72	01/03/19 16:34	442,04	21,14	37,23
01/03/19 13:39	477,04	20,46	29,74	01/03/19 16:39	444,04	21,13	37,25

01/03/19 16:44	570,04	21,09	36,13	01/03/19 19:39	590,04	21,39	35,19
01/03/19 16:49	573,04	21,12	36,11	01/03/19 19:44	596,04	21,44	35,17
01/03/19 16:54	570,04	21,14	36,08	01/03/19 19:49	610,04	21,47	35,13
01/03/19 16:59	572,04	21,14	36,08	01/03/19 19:54	610,04	21,51	35,04
01/03/19 17:04	580,04	21,14	36,06	01/03/19 19:59	619,04	21,53	34,97
01/03/19 17:09	581,04	21,14	36,06	01/03/19 20:04	617,04	21,55	34,83
01/03/19 17:14	581,04	21,14	36,05	01/03/19 20:09	619,04	21,57	34,77
01/03/19 17:19	575,04	21,15	36,01	01/03/19 20:14	619,04	21,58	34,67
01/03/19 17:24	585,04	21,15	35,98	01/03/19 20:19	617,04	21,59	34,56
01/03/19 17:29	585,04	21,16	35,99	01/03/19 20:24	611,04	21,61	34,46
01/03/19 17:34	585,04	21,16	35,95	01/03/19 20:29	610,04	21,61	34,4
01/03/19 17:39	582,04	21,16	35,9	01/03/19 20:34	612,04	21,62	34,36
01/03/19 17:44	581,04	21,17	35,86	01/03/19 20:39	609,04	21,61	34,41
01/03/19 17:49	579,04	21,17	35,83	01/03/19 20:44	604,04	21,62	34,41
01/03/19 17:54	578,04	21,16	35,81	01/03/19 20:49	603,04	21,66	34,33
01/03/19 17:59	584,04	21,16	35,78	01/03/19 20:54	599,04	21,68	34,28
01/03/19 18:04	580,04	21,16	35,79	01/03/19 20:59	593,04	21,69	34,2
01/03/19 18:09	579,04	21,17	35,74	01/03/19 21:04	593,04	21,71	34,13
01/03/19 18:14	569,04	21,17	35,64	01/03/19 21:09	586,04	21,73	33,97
01/03/19 18:19	557,04	21,17	35,53	01/03/19 21:14	579,04	21,73	33,89
01/03/19 18:24	544,04	21,19	35,46	01/03/19 21:19	581,04	21,72	33,86
01/03/19 18:29	536,04	21,19	35,38	01/03/19 21:24	577,04	21,71	33,78
01/03/19 18:34	519,04	21,19	35,27	01/03/19 21:29	574,04	21,72	33,71
01/03/19 18:39	518,04	21,19	35,28	01/03/19 21:34	550,04	21,75	33,52
01/03/19 18:44	519,04	21,2	35,28	01/03/19 21:39	543,04	21,74	33,44
01/03/19 18:49	528,04	21,21	35,28	01/03/19 21:44	535,04	21,72	33,39
01/03/19 18:54	532,04	21,24	35,26	01/03/19 21:49	524,04	21,71	33,34
01/03/19 18:59	534,04	21,27	35,25	01/03/19 21:54	519,04	21,7	33,32
01/03/19 19:04	546,04	21,29	35,22	01/03/19 21:59	516,04	21,69	33,33
01/03/19 19:09	547,04	21,31	35,17	01/03/19 22:04	515,04	21,68	33,33
01/03/19 19:14	551,04	21,33	35,17	01/03/19 22:09	516,04	21,68	33,35
01/03/19 19:19	559,04	21,33	35,18	01/03/19 22:14	510,04	21,67	33,32
01/03/19 19:24	586,04	21,35	35,24	01/03/19 22:19	503,04	21,67	33,27
01/03/19 19:29	576,04	21,37	35,16	01/03/19 22:24	497,04	21,68	33,17
01/03/19 19:34	582,04	21,38	35,16	01/03/19 22:29	493,04	21,68	33,11

01/03/19 22:34	493,04	21,68	33,07	01/04/19 8:17	456,04	21,44	32,34
01/03/19 22:39	485,04	21,69	33,02	01/04/19 8:22	471,04	21,61	31,58
01/03/19 22:44	489,04	21,7	32,97	01/04/19 8:27	469,04	21,59	31,6
01/03/19 22:49	482,04	21,7	32,93	01/04/19 8:32	464,04	21,57	31,63
01/03/19 22:54	476,04	21,72	32,9	01/04/19 8:37	462,04	21,57	31,62
01/03/19 22:59	472,04	21,81	32,82	01/04/19 8:42	465,04	21,58	31,58
01/04/19 5:52	469,04	21,92	32,71	01/04/19 8:47	459,04	21,58	31,54
01/04/19 5:57	473,04	21,94	32,65	01/04/19 8:52	465,04	21,57	31,59
01/04/19 6:02	477,04	21,88	32,65	01/04/19 8:57	461,04	21,56	31,62
01/04/19 6:07	477,04	21,82	32,67	01/04/19 9:02	457,04	21,56	31,64
01/04/19 6:12	472,04	21,78	32,66	01/04/19 9:07	453,04	21,55	31,69
01/04/19 6:17	471,04	21,75	32,62	01/04/19 9:12	457,04	21,54	31,73
01/04/19 6:22	470,04	21,72	32,56	01/04/19 9:17	455,04	21,52	31,79
01/04/19 6:27	464,04	21,7	32,5	01/04/19 9:22	455,04	21,49	31,79
01/04/19 6:32	465,04	21,7	32,46	01/04/19 9:27	457,04	21,47	31,82
01/04/19 6:37	461,04	21,7	32,4	01/04/19 9:32	451,04	21,46	31,88
01/04/19 6:42	463,04	21,69	32,37	01/04/19 9:37	451,04	21,44	31,93
01/04/19 6:47	464,04	21,67	32,34	01/04/19 9:42	449,04	21,43	31,97
01/04/19 6:52	460,04	21,66	32,31	01/04/19 9:47	453,04	21,42	32,02
01/04/19 6:57	463,04	21,64	32,28	01/04/19 9:52	453,04	21,4	32,06
01/04/19 7:02	462,04	21,62	32,27	01/04/19 9:57	447,04	21,39	32,11
01/04/19 7:07	456,04	21,6	32,27	01/04/19 10:02	443,04	21,37	32,15
01/04/19 7:12	455,04	21,58	32,24	01/04/19 10:12	448,04	21,38	32,17
01/04/19 7:17	461,04	21,57	32,25	01/04/19 10:17	441,04	21,37	32,18
01/04/19 7:22	459,04	21,56	32,24	01/04/19 10:22	446,04	21,36	32,2
01/04/19 7:27	456,04	21,54	32,26	01/04/19 10:27	451,04	21,35	32,23
01/04/19 7:32	452,04	21,53	32,27	01/04/19 10:32	451,04	21,34	32,26
01/04/19 7:37	457,04	21,51	32,27	01/04/19 10:37	451,04	21,33	32,3
01/04/19 7:42	457,04	21,49	32,29	01/04/19 10:42	451,04	21,31	32,33
01/04/19 7:47	451,04	21,49	32,3	01/04/19 10:47	451,04	21,3	32,36
01/04/19 7:52	458,04	21,49	32,29	01/04/19 10:52	446,04	21,3	32,38
01/04/19 7:57	457,04	21,49	32,29	01/04/19 10:57	445,04	21,29	32,41
01/04/19 8:02	458,04	21,48	32,31	01/04/19 11:02	445,04	21,27	32,44
01/04/19 8:07	457,04	21,47	32,32	01/04/19 11:08	451,04	21,26	32,48
01/04/19 8:12	458,04	21,45	32,33	01/04/19 11:12	451,04	21,27	32,49

01/04/19 11:17	446,04	21,28	32,5	01/04/19 12:07	442,04	21,18	32,74
01/04/19 11:22	441,04	21,27	32,52	01/04/19 12:12	442,04	21,2	32,75
01/04/19 11:27	443,04	21,27	32,55	01/04/19 12:22	444,04	21,2	32,76
01/04/19 11:32	449,04	21,26	32,58	01/04/19 12:27	444,04	21,2	32,77
01/04/19 11:37	446,04	21,24	32,61	01/04/19 12:32	445,04	21,2	32,79
01/04/19 11:42	445,04	21,23	32,63	01/04/19 12:37	444,04	21,19	32,81
01/04/19 11:47	440,04	21,22	32,66	01/04/19 12:42	441,04	21,18	32,84
01/04/19 11:52	444,04	21,21	32,68	01/04/19 12:47	445,04	21,17	32,87
01/04/19 11:57	444,04	21,19	32,71	01/04/19 12:52	441,04	21,16	32,88

Table 9 Data for Case-study No. 1

T: Temperature
H: Humidity