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Towards a Dark Factory – Leveraging multidimensional twins in a manufacturing metaverse

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Introduction

The history of industry can be understood as the advancement of the way that humans produce goods and services. Throughout this progress several industrial revolutions again and again harnessed new energy sources, reorganized labor, and ultimately increased productivity. Today new market pressures such as the trend for mass customization and climate change force businesses to innovate further [89]. The fourth industrial revolution is a means to overcome these challenges by thoroughly connecting production resources through digital technologies. This revolution is still well underway and focus of many research activities worldwide [90]. (Figure 22)

In the wake of the current fourth industrial revolution the concept of the Smart Factory was introduced, i.e. a factory that is highly automated and smartly connected [91]. By taking this idea one step further, one arrives at the concept of a so-called Dark Factory, also called a lights-out factory [92], [93]. In this kind of factory, the degree of automation is so high, that human oversight is no longer necessary, and the lights can be turned off, hence the name. Such a fully automated production facility, provided that it can retain or even increase flexibility, poses a substantial advantage in the modern competitive production environment. Not only is it able through smart communication among its resources to handle small lot sizes and customized, heterogenous production orders [94], [95], but it also has a higher production rate and is highly efficient. Automation to such an extent has even been described as "the holy grail of manufacturing" [92]. It is therefore an attractive goal to work towards this vision for producing businesses.

However, the idea of the Dark Factory is yet to be widely implemented and the path towards its implementation seems unclear. Businesses that want to work towards achieving the vision can find themselves quickly lost in a wide variety of different products and technologies. This study aims to alleviate this. It offers guidance by providing information and tools to answer the following questions for prospective Dark Factories:

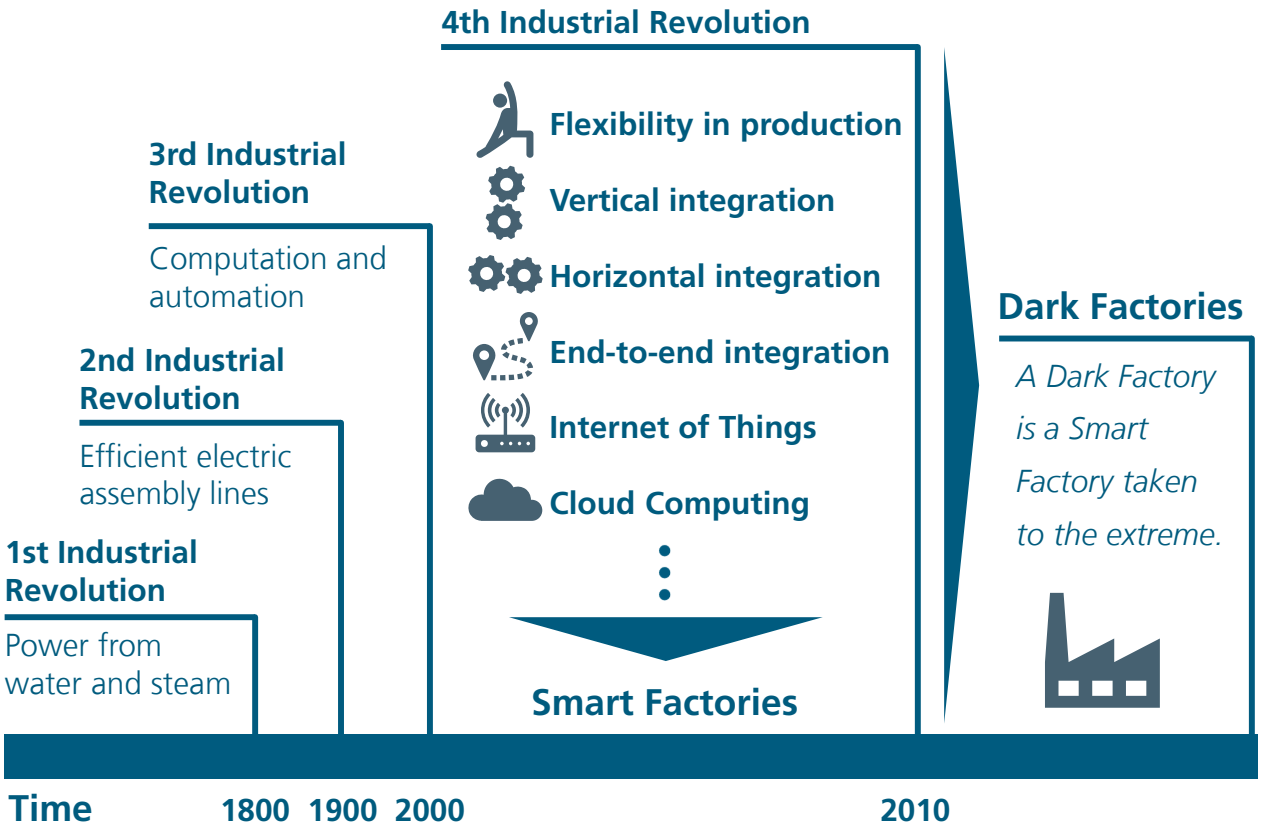

Figure 22: Smart and Dark Factories in the context of past and current industrial revolutions.

1. How close is a given factory to the goal of the Dark Factory?
2. Which technologies are or will be relevant for implementing the vision of the Dark Factory?

Taken together these questions can influence the direction of development efforts towards the Dark Factory. Section The next section explains the methodology and structure of the study to answer these questions, and describes which deliverables were elaborated. The deliverables are then explained in more detail and highlight how businesses can use them. The report concludes with a short summary of how the study could support companies on their way towards the vision of the Dark Factory.

Study deliverables and methodology

The research for this study was conducted in three phases with two main deliverables as results. The employed procedure is visualized in Figure 23.

The three phases of the study were as follows:

Phase I: First a literature review was conducted, in which sources concerning the Dark Factory were gathered in a catalogue and evaluated. Then they were used to extract the dimensions of the maturity model, i.e. the aspects in which factories progress towards a Dark Factory.

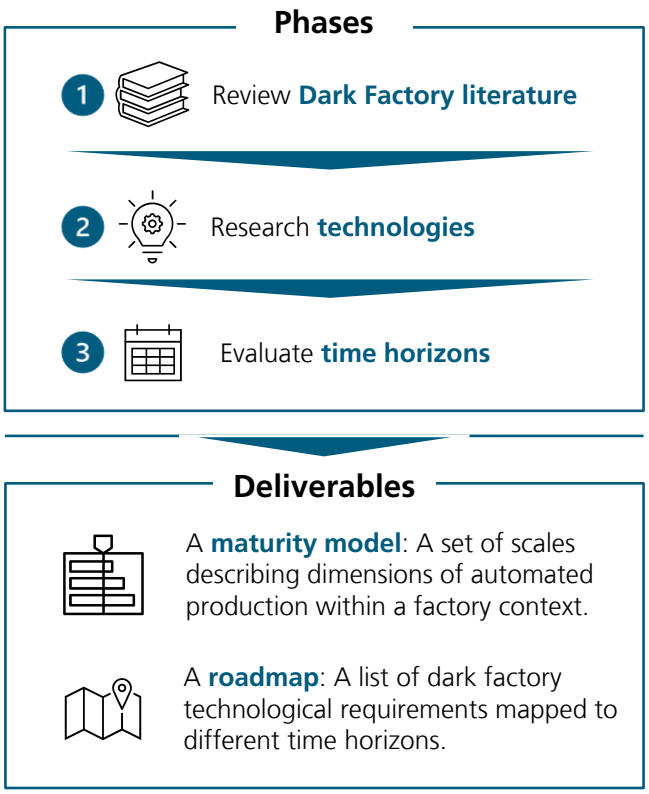

Figure 23: Phases and deliverables of the Dark Factory study.

Phase II: In the second phase the maturity model was finalized by adding stages and capabilities to the dimensions. Furthermore, concrete technologies were researched from literature as well as from exchanges with the community that for each dimension help achieve these capabilities. They were additionally mapped on to the ICNAP topic fields.

Phase III: In the last phase time horizons were defined that represent categories for the future availability of a technology. Each technology was then assigned to these time horizons in order to draw the roadmap for the Dark Factory.

Over the course of the study two main deliverables were achieved:

A maturity model: This model includes the dimensions, stages, and capabilities of a Dark Factory and captures the difference in development between traditional factories and smart, highly autonomous Dark Factories. It is a tool to assess for a given factory how close it is to the goal of the true Dark Factory in terms of capabilities. It can be used to deduce in which dimensions more work needs to be done .

A roadmap: In order to focus efforts in the right direction and not miss important research trends, the roadmap can be used. It organizes technologies that are important in the Dark Factory context into time horizons and thus gives them a chronological order. By using this tool future technologies and competencies can be acquired at the right time as they are needed in order to reach the capabilities that are specified within the maturity model. To that end the roadmap is also organized along the same dimensions as the latter.

Maturity model

The maturity model consists of six dimensions that represent independent aspects of a factory, in each of which progress towards a Dark Factory can be made. Each dimension is partitioned into stages, which are to be understood as a level a factory can reach for that given dimension. In order to reach such a stage a factory needs to support the capabilities associated with the given stage as well as the capabilities of the stages below it. The model is shown in Figure 24.

In the following, the model's dimensions, stages, and capabilities are described.

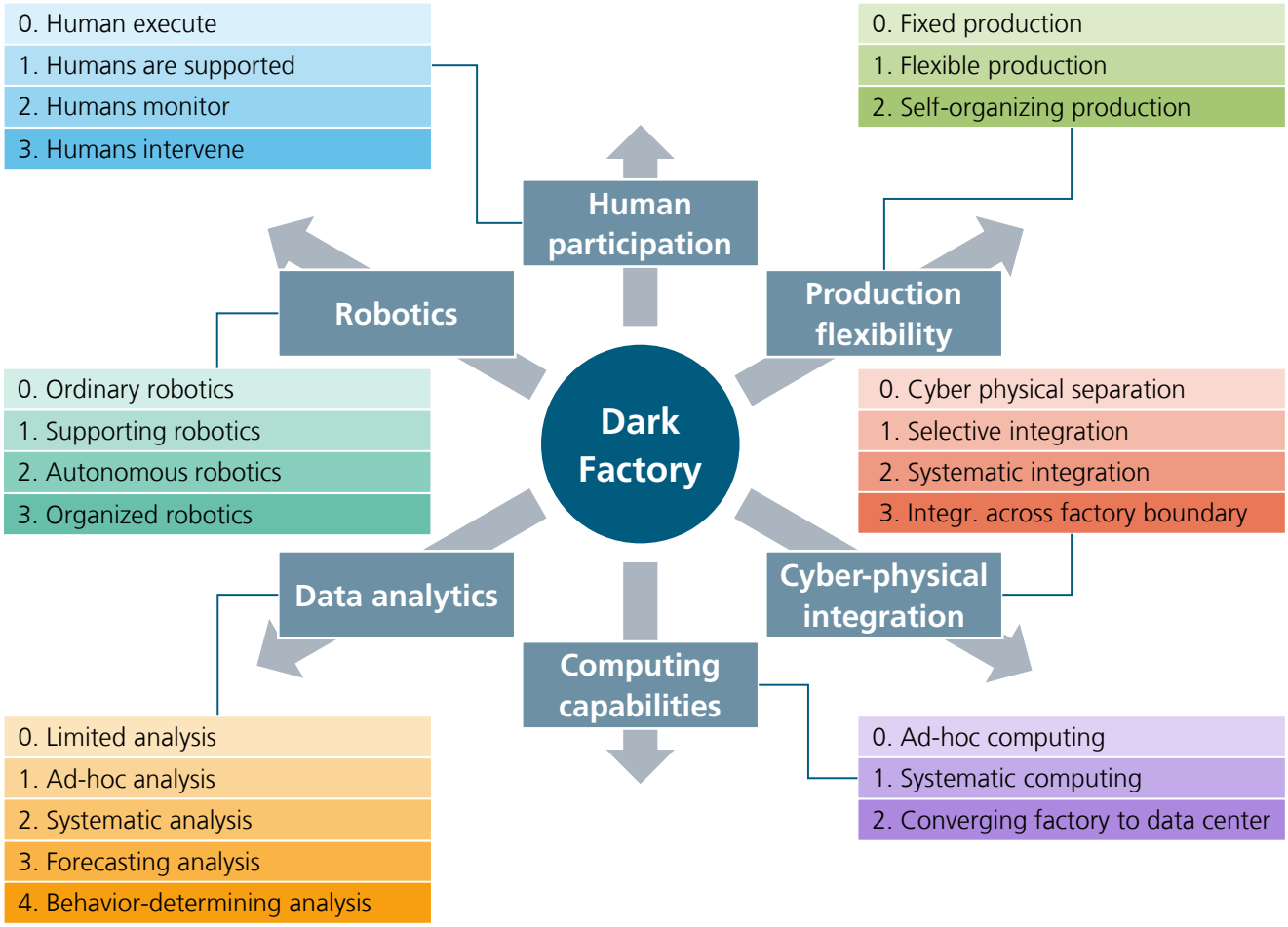

Figure 24: The dimensions and stages of the Dark Factory Maturity Model .

Human participation: This dimension describes the extent to which humans take part in the production process, i.e. whether they act executively or in a managing capacity. While the motivation behind the Dark Factory envisions a future without any human involvement, it remains unclear whether this will come to pass. However, as the push for further automation progresses the role of human labor will change. The stages of this dimension are as follows:

1. **Stage 0 – Humans execute:** The majority of the work is done through human labor. There are no extraordinary capabilities on this stage.
2. **Stage 1 – Humans are supported:** While a significant portion of the workload is still handled by humans, the factory supports them through functions such as remote access, predictive maintenance planning and proposals for self-optimization.
3. **Stage 2 – Humans monitor:** The majority of the workload is handled by automated systems of the factory, with humans playing a supporting role. The capabilities here include remote control, automated procurement, automated work setup and automated execution of production.
4. **Stage 3 – Humans intervene:** The factory runs autonomously, and humans only have to intervene in case of serious faults and emergencies. At this stage the factory supports functions such as automated maintenance and fully automatic self-optimization.

Production flexibility: This dimension expresses how well the factory handles process changes, e.g. due to small lot sizes. With the trend for mass customization being a major driver behind the Industry 4.0 movement [94], it remains important that factories will be able to meet this trend. Therefore, it is not enough to increase the degree of automation in a mass production scenario, but also to apply the same level of automation to highly customized products and parts. A factory can reach the following stages within this dimension:

1. **Stage 0 – Fixed production:** Within the factory it is difficult and expensive to change processes and produce new products. There are no extraordinary capabilities associated with this stage.
2. **Stage 1 – Flexible production:** Processes that are executed within the factory can be changed quickly and with relatively low efforts. Functions at this level include the ability to manufacture multiple different products on the same production line and active process planning support from intelligent systems within the factory.
3. **Stage 2 – Self-organizing production:** On this stage the systems within the factory plan and execute production processes autonomously based on given requirements. The lot size plays a negligible role and most if not all aspects of planning, such as processes, logistics and shopfloor management are organized by the factory itself.

Cyber-physical integration: This dimension describes the level of integration between the realms of the physical and the virtual, e.g. in the context of digital twins or Cyber-Physical Systems. By leveraging the strengths of virtual and software components, a factory can benefit from smarter and more connected systems, which in turn can run the factory more autonomously. Thus, the progress along this dimension constitutes progress towards a Dark Factory. In detail the following stages were identified along this dimension:

1. **Stage 0 – Cyber-physical separation:** The physical and the virtual realm are not connected within the factory, therefore no capabilities are available in this regard.
2. **Stage 1 – Selective integration:** Systems that integrate the physical and the virtual are in use on a per-need basis, such as product digital twins or Cyber-Physical Systems in the form of machine tools.
3. **Stage 2 – Systematic integration:** Not only are digital twins and Cyber-Physical Systems commonplace for products and machines, but they are also integrated with each other and communicate. Important aspects of the factory can be controlled thus by interfacing with the virtual world.
4. **Stage 3 – Integration across factory boundaries:** The factory is integrated beyond its own inner system in a virtual ecosystem, for example like the metaverse.

Computing capabilities: This dimension assesses the capabilities of the factory in terms of computation, e.g. on-premises, on the edge, or in the cloud. As the need for computational resources increases with the use of more sophisticated data processing techniques and the handling of higher data volumes, the data center and the factory converge more and more. The dimension of computing capabilities represents this development and consists of the following stages:

1. **Stage 0 – Ad-hoc computing:** There are no extraordinary computational resources in use within the factory.
2. **Stage 1 – Systematic computing:** The factory makes extended use of computing facilities, with a mixture of on-premises, edge, and cloud computing capabilities. Within its capabilities is also secure data transmission, storage and processing.
3. **Stage 2 – Factory to data center convergence:** The factory supports the functions of a high-end data center. The capabilities include hyperscaling of resources, big data and real-time support.

Data analytics: This dimension gauges the degree of how much of decision-making is supported by data analytic techniques, such as AI and machine learning. As data is not an end in itself but rather a tool to make informed decisions, methods and tools are needed to gain knowledge from the data. The discipline of data analytics can be used to accomplish this and is therefore an integral part of a Dark Factory. The stages are:

1. **Stage 0 – Limited analysis:** Data analytics are not used in a meaningful way.
2. **Stage 1 – Ad-hoc analysis:** Simple analytics methods are used on a per-need basis. They mostly concern the area of descriptive data analytics.
3. **Stage 2 – Systematic analysis:** Data analytics on this stage is an automated process that leads to systematic insights about the production process. The capabilities are of the realm of diagnostic data analytics.
4. **Stage 3 – Forecasting analysis:** Within the factory predictive data analytics is used to make estimations about the future which inform the behavior and the decisions during production.
5. **Stage 4 – Behavior-determining analysis:** Prescriptive data analytics is used to govern behavior autonomously within the factory.

Robotics: This dimension signifies the extent as to which human labor is replaced by cooperative or autonomous robots. As human involvement decreases on the path towards more automation, the physical labor needs to be taken up by machines and robots. A factory therefore needs to progress along this dimension on its way to the Dark Factory. In doing so it reaches the following stages:

1. **Stage 0 – Standard robotics:** There are no special abilities concerning robotics within the factory that go beyond basic functions.
2. **Stage 1 – Supporting robotics:** Robots are actively used to support human workers. Examples include cobots and autonomous guided vehicles (AGVs).
3. **Stage 2 – Autonomous robotics:** At this stage robots within the factory act as autonomous agents that fulfill general tasks assigned by human supervisors.
4. **Stage 3 – Organized robotics:** Ultimately, the robots within a Dark Factory are self-organized, with little or no human intervention.

Roadmap

The roadmap identifies technologies, trends and research topics that are relevant for the foreseeable future as factories evolve towards more automation and autonomous behavior. It can indicate where research efforts should be placed and what the expected technological advancement in a given Dark Factory might look like. Naturally the more the timeframe for predictions stretches into the future, the larger the cone of uncertainty grows. Making confident assumptions thus quickly becomes difficult. To meet this problem three different time horizons have been defined to indicate how quickly a given technology is expected to be widely available. These time horizons are as follows:

Market ready: As the name implies, technologies that fall within this horizon are already widely available and in use by many market players. The technology readiness level [96] for these technologies falls within level 8 and 9. Thus there is at least one product or service on the market that implements the given technology. These products help factories progress along the dimensions to reach the stages and capabilities described in the maturity model. Some examples are listed in Table 3. The references for each technology are examples that highlight their active use within manufacturing and elsewhere.

Short term: Technologies that are already proven to be promising in the context of Dark Factories, either through working prototypes or extensive research, fall within this time horizon. As a rule, a technology can be classified in this area id commercial solutions are foreseeable, for example because a startup is working on a corresponding product, or if application-oriented research has proven the feasibility of the technology. Therefore, these technologies generally have a readiness level between 4 and 7 and can be expected to be available in the upcoming years. Table 4 lists some examples. Here, the references illustrate technologies that are actively being researched, with market readiness in short term reach.

Long term: Finally, there are technology trends and topics that are expected to play an important role in the development of the vision of the Dark Factory. However, they are not yet market ready or still in early stages in the context of production. Their technology readiness levels are between 1 and 3 wich means they are either in the proof-of-concept or early research phase. Some of these trends are listed in Table 5. The references show that these technologies are currently conceived but not soon to be applied in real production environments.

Dimension	Technologies and trends
Human participation	Secure data governance [97], remote commissioning [98] and maintenance [99], pay-per-use [100] and pay-per-part [101]
Production flexibility	Wifi 5G and 6 [102], resource hyperscaling [103], predictive maintenance [104]
Cyber-physical integration	Augmented [105] and virtual [106] reality, ready-made DT tools [107], real-time tracking [108], standardized protocols [109], IoT databases [110]
Computing capabilities	Cloud [111] & edge [112] computing, hybrid cloud storage [113], containerization [114], secure cloud architectures [115], secure data at rest [116] and in transit [117], custom trained AI [118], big data processing [119], Industrial Internet of Things [120], environmental sensing [121], computational sensors [122]
Data analytics	Generative AI [123], semantic data models [124], standardized information models [125], high frequency data acquisition [126]
Robotics	Cobots [127], automated guided vehicles [128], autonomous mobile robots [129], tracking and tracing [130], M2M communication [131]

Table 3: Market ready roadmap trends and technologies.

Dimension	Technologies and trends
Human participation	Emotion recognition [132], gesture-based interfaces [133], human oversight in AI [134]
Production flexibility	Manufacturing-as-a-service [135], cloud manufacturing [136], Smart retrofitting [137]
Cyber-physical integration	DT standards [138], physical process models [139], wireless sensing [140], DT monetization [141], real-time DT [142]
Computing capabilities	Real-time data acquisition [143], AI-on-device [144], DT-on-edge [145]
Data analytics	Data monetization [146], data exchange spaces [147], AI-integrated DTs [148], AI integrated sensors [149], explainable AI [150]
Robotics	Plug-and-Play Robotics [151], cloud-Integrated robotics [152], cyber-physical systems [153]

Table 4: Short term roadmap trends and technologies.

Dimension	Technologies and trends
Human participation	Complete horizontal and vertical integration [154]
Production flexibility	Self-organized systems [155], AI-based production planning and scheduling [156]
Cyber-physical integration	Metaverse [157], ambient IoT [158]
Computing capabilities	IT/OT-convergence [159], quantum computing [160], virtual control [161]
Data analytics	Qualified (trustworthy) AI [162]
Robotics	Human-level general purpose robotics [163]

Table 5: Long term roadmap trends and technologies.

Conclusion

Dark Factories hold many promises for future production scenarios, with higher productivity at the top of the list. Whether or not the concept can fulfil these promises depends on whether it can be widely and safely implemented. To that end a path needs to be drawn that makes the implementation feasible. With the outcomes of this study drawing this path for a given organization has become easier. The proposed maturity model and technology roadmap can indicate the progress of a factory towards a Dark Factory, which can help companies identify room for development within their own production facilities. Companies are enabled to formulate their own vision of a Dark Factory and receive guidance during the definition of steps towards this defined vision.

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