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Distributed manufacturing under pandemic conditions

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supervised by
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Vienna, 11.03.2021

Affidavit

I, **MAG. DR. STEFAN VIEWEG**, hereby declare

1. that I am the sole author of the present Master's Thesis, "DISTRIBUTED MANUFACTURING UNDER PANDEMIC CONDITIONS", 67 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

The thriving globalization conditions fostered the emergence of distributed manufacturing over the past decades, covering almost all of the industries, regions, and economies. The international and complex network of manufacturers, sub-manufacturers, and integrated logistics companies organized the industrial throughput to an almost perfect extent.

Nevertheless, the disruptive event of the COVID-19 pandemic appearing in 2020 changed the rules of the game. This pandemic took most of the countries and organisations by surprise, with the tragic consequences of 120 million infections and almost 3 million deaths worldwide until March 2021.

This thesis starts off with a brief introduction of the history of distributed manufacturing and economic internationalization. Then, an overview of the various pandemics of the past centuries is presented, with special focus on their economic consequences. Special attention of the analysis is put on the challenges from the current COVID-19 pandemic.

Generally, the risks and challenges that arise in this crisis are manifold and range from immediate health risks, isolation risks as well as disruptive changes in the supply chain and manufacturing setups. This thesis focusses on suggesting and analysing a broad range of mitigation action that can be implemented to meet, solve or ease them. Resilience, redundancy and flexibility are the factors of robustness that play an important role in crisis management. Building up robustness and resilience is proposed by applying corrective and preparative action for a wide range of production factors (people, material, processes, supply chain etc.) and a variety of risk classes (health, isolation, lockdown). In order to exemplify the approach, two case scenarios with corrective actions are analysed and presented.

The thesis closes with an outlook on how the mitigation actions can tactically serve as a set of corrective and preventive actions in order to improve the economic position. Focus is given on how to prepare for future challenges by a strong emphasis on resilience and robustness of the supply and value chains in distributed manufacturing.

Distributed manufacturing under pandemic conditions

by Dr. Stefan Vieweg (08403428)

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1. Introduction

Distributed engineering and manufacturing represent an integral part of today's international economic and business relations. The model represents one of the cornerstones of the economic development throughout the last centuries, not only in first level economies such as Europe and North America, but also in the developing regions of the world. This approach is observed in many economic activities world-wide and has become the generic model in wide range of international business activities. Variations thereof populate along the following dimensions: business area, geography, manufacturing sites, assembly sites, products, manufacturing degree, engineering, finance, planning, logistics etc. The degree to which distributed manufacturing has evolved depends on these factors.

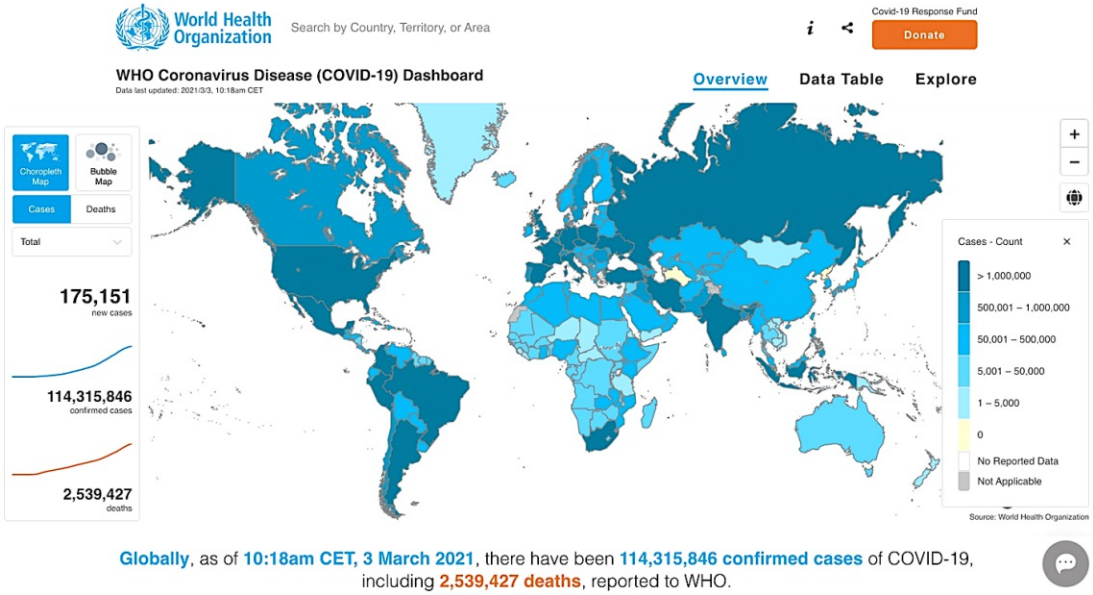

Figure 1, COVID-19, global cases [1]

With very few exceptions (North Korea, Venezuela), almost all countries have supported and adopted this framework of international division of labour. The international community and states have even created and advocated this by the implementing international organizations (WTO, OECD, EU, NAFTA, ASEAN, TPP, RCEP) supporting cross-border activities of various forms by regulating customs, taxation, logistic frameworks.

This alignment process started out in the 16th century (triangular trade) and culminates in the early 2020s. Up until now there were few indications or signs of a slow down or even a reduction of this phenomenon. There were shifts in consumer and production patterns, even financial crises, but the general direction of the internationalization was persisting over the centuries.

As of now, in early 2021, the outbreak of the COVID-19 virus infection has quickly evolved into a world-wide pandemic of unprecedented scale. We are facing a disruptive event that is currently causing the near breakdown of the economic activities around the world. Social environments, economies and businesses are more or less in turmoil and disorder. As of today, almost no country, city, or company has been spared of the serious medical, organisational, financial, and social consequences of the pandemic. The extent to which the countries are affected may vary. The pandemic cycles shift from case to case. However within a bracket of 6-9 months they all are experiencing the serious effects of the outbreak. The consequences at this point in time are estimated at least as severe as the ones from the financial crises in 2007/08. The WHO reports more than 102 million cases with a number of deaths coming to over 2,2 million, it is expected that the number of cases increases over the next months.

The challenges arising from this COVID-19 are manifold. This thesis will focus on how to cope with the particular management challenges that distributed manufacturing organisations are currently facing. First, an outline of the development of manufacturing and trade throughout the centuries will be given. Covering from simple barter and trading the development into modern 21st century manufacturing concepts will be depicted. Then, chapter 2 deals with pandemic conditions, examples of previous pandemics will be described and the effects on the economic development will be looked at. The thesis will then turn to the current pandemic we are confronted with: COVID-19. General risks and health management action to curb the infections will be presented.

This thesis will also cover the challenges modern management is facing, with particular emphasis on COVID-19 and distributed manufacturing a framework for describing the necessary challenges will be presented with emphasis on mitigating the risks that are companies and organisations face. Special focus will be put on the production factors such as labours, products, information technology, and supply chain.

Special attention on distributed manufacturing and the related risks will be given. Distributed organisations face risks regardless of the current pandemic. Manufacturing is very complex, and risks are numerous: Markets conditions and demand may shift, workforce with related cost might change over time, supply chain condition might change. The following chapter will then deal with how to mitigate the risks that are related to and coming from the current pandemic with corrective and preventive actions. For this purpose the paper will introduce categories for the risks and risk mitigation. This includes health risks, that are concerning people's well-being; isolation

risks that relate to the local organisation unit, as well as lockdown risks that deal with how the organisational units deal with each other (network of companies, sites or organisations). The risks and mitigation action will then be related to production factors (people, products, equipment, information technology) to come up with a framework for coping with these issues. Factors like the size of the organisation or the effort with which the mitigation can take place are presented. The severity and effort to go with the mitigation action is included in the analysis. The thesis closes with some example scenarios on how to tackle the risks we are confronted with by the pandemic.

Furthermore, the thesis concludes with reflections and a positive outlook on how the risk mitigation actions can be used to the benefit of the companies and countries. The resulting strengthening of the organisation in order to find new business prospects is a chance in the crisis.

Furthermore, given the action taken during this pandemic crisis we are now disposing of a blueprint at hand that can help to cope with future crises.

The perspective in chapter 5 closes with the competitive advantage the companies (and countries) can take from this pandemic. Chapter 6 gives a summary of the findings and the conclusion of this thesis.

2. Manufacturing in the 21st century

This chapter will introduce a brief history of manufacturing. Focus hereby is to show that trade, logistics, and distributed manufacturing are key concepts that have been around since the beginning of production and trade throughout the history of civilization.

Advances in technology, computerization, data networking as well as logistic optimizations however have led to tremendous efficiency gains and developments, particularly in the 20th and 21st century. Further to the development throughout the centuries, some of the involved risks and challenges are described.

2.1 History of trade and manufacturing

Ancient history and civilization records show that at first production was strongly localized and committed to the own immediate and instantaneous demand of the population [2]. People produced for their immediate needs and their direct surroundings and neighbourhoods. Soon the production capabilities began to exceed the needs and requirements of the local tribes or organisations. In addition, food processing techniques and in particular food preservation techniques (drying, salting) were additional and essential contributions.

Barter, trading and exchange evolved and resulted in considerable exchange amount of trade and wealth [3]. Distributed manufacturing (and trade) initially evolved around the primary materials such as metals (copper), minerals (salt), or around basic resources or building material (stone, quarries). However, the degree of production technology with respect to processing and assembly was rather basic.

One of the very successful and remarkable organizations were the 'Fugger-Family' from Augsburg in the south of Germany. The Fugger family took its origin in the 14th century, when in 1367 Hans Fugger moved to the city of Augsburg and founded one of the most remarkable ventures in German business history [4]. Over the next generations and centuries, the family ventures evolved into the biggest European trader in the millennium. His early ventures led him to Venice where Fugger studied trading practice on site. In the 16th century Jakob Fugger then perfected the trading business and established a trading and manufacturing empire reaching from the south of Germany, Venice, the Baltic Sea to Spain, Portugal until India. Many establishments in all over Europe were founded and trade basic materials (copper, salt, cotton) were skilfully traded with considerable profits. One of the particularities of the Fugger empire is not only the successful trading

venture, but also the plentiful ties with the catholic church and the German emperors, networking at its perfection. In order to secure and extend the business ties the Fugger developed banking and trade finance facilities to near perfection. Money lending, money transfers and securities were introduced and amplified the success in their business ventures. In today's currency the wealth of Jakob Fugger (1459-1525) amounts to the amazing amount of 400 billion USD [5], approximately 350 billion EUR. Contemporary wealth pales in comparison. It has to be pointed out that the family invested considerable amounts of their wealth in public housing, art and museums, many of which still are in place today, after centuries. The Fugger trust still operates social housing projects at a remarkable standard, the wealth (partly) preserved over centuries.

The activities of the Fugger were predominantly concentrated in continental Europe. Advances in ship building and navigation as well as the curiosity of researchers and adventurers were the main drivers to discover new parts of the world. The first colonial powers evolved. The United Kingdom, Spain, Netherlands, Portugal and Italy were among the first countries (or kingdoms) to reach out for additional land, power, and economic wealth. The consequences were tremendous. The exchange of goods, mostly between colonial Africa and Asia increased and reached considerable levels, even by today's standards. By the 18th century the colonial trade evolved and was established between Africa, North America and some South American colonies.

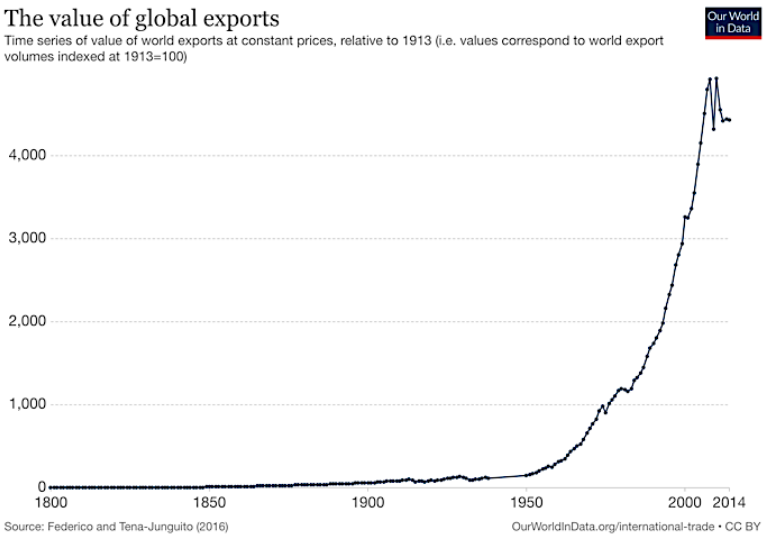

Figure 2, Global export development, in USD (1800-2014) [6]

The end of the 19th century brought change and several developments lead to a new step of distribution from then on. The reasons were manifold. Firstly, the political independence of the former colonies increased. After two world

wars in the 20th century, most of the former colonies were granted independence in the subsequent decades of the end of World War II (after 1945) India, Malaysia, Indonesia and most of the former African colonies became independent. However, dependencies between were still prevailing. Many of the economies of the former colonies are still closely tied to the former colonial powers.

A similar efficiency increase was achieved in land transport. Transport infrastructure was established in most of the industrial countries. Train lines were built, canals were dug, roads were constructed. After the introduction of cars, the road networks were increased everywhere. These physical pathways form an integral part of logistics. However, the organizational aspect of logistics with time management, procedures, international transport agreement, handling and transport standards as well as intermediate stocks added to the efficiency of transport, in general.

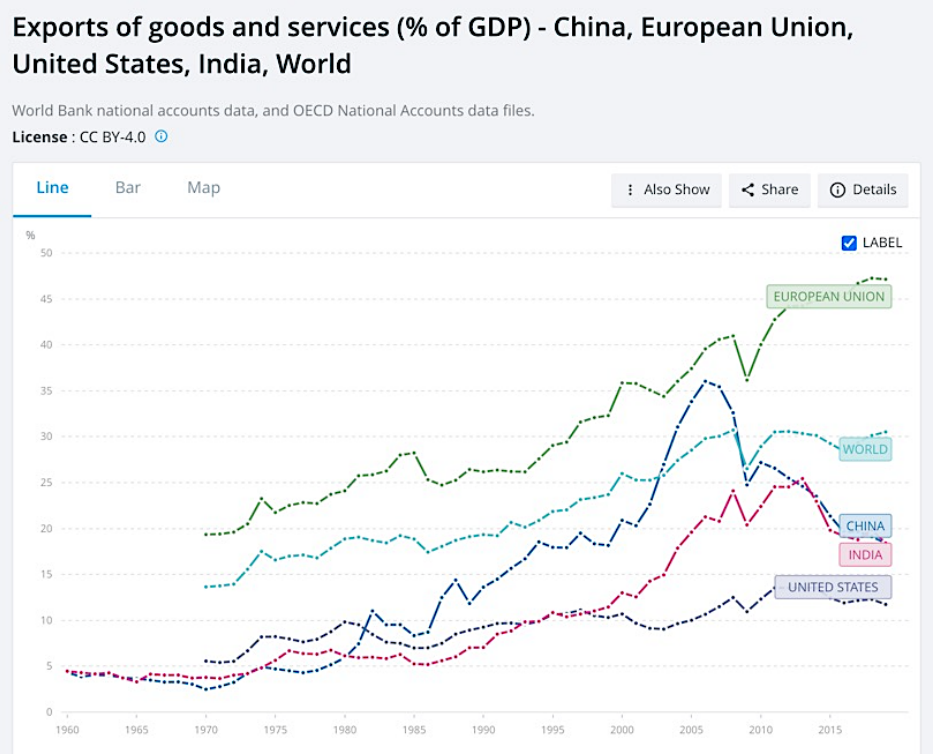

Figure 3, Export of goods and services (1960-2019) [7]

Eventually, a tremendous world-wide logistics network is at work, for both consumer or private transport and delivery as well as for business logistics between producers, suppliers, and customers and production networks world-wide.

The value of global exports has been increasing ever since. Figure 3, Export of goods and services (1960-2019) describes the increase of the world global exports and their increase rates. Even by taking into account some of the

obvious statistical inconsistencies concerning the availability and accuracy of the base data over the centuries, the message is clear and shows a tremendous increase of world trade starting right after the 1950s. The contributors of this development are shown below chart showing the export share of countries. Starting off with Western Europe and the United States, new exporting champions such as India and China entered the world stage at the beginning of the second millennium, their domination continues into the 21st century. Predictions are difficult by nature, but the dominance of Asian countries in production and the rise of Africa as both consumer market and manufacturing region are a reasonably sound notion. This leaves Europe and North America with the arduous task of refining their industries while not falling behind the developments in Asia.

2.2 Industrial revolution and free trade

The Industrial revolution was started in the 18th century in Europe. The invention of the stream engine by J. Watts represents the starting point. Simply put, this invention made it possible to provide energy at any possible location, where and when it would be needed. This shift in paradigm had tremendous consequences. Up until then energy or power was only available through manpower (muscles) or natural resources. Wind and water were the primary sources, machines were powered directly, power was not 'transportable'. All this was very localized and restricted to the respective accessibility and seasonal availability.

Steam power allowed to set up shop and power wherever needed and thus created a general principle of the industrial revolution. These engines were combustion powered, thus engine manufacturers emerged, but also fuel (first wood, then oil/petrol) was needed on a large scale. The consequences of this development were considerable, for all level and players in society and environment. The first time in history goods were available on a large scale, in sufficient quantities and at acceptable qualities. Factories opened near cities. Firstly, to be near to the customers and consumers. Secondly, the workforce employed in the factories were recruited from the cities. Needless to say, that this development also created conflicts about the distribution of wealth, mainly between producers and workers. The early 20th century is characterized by this conflict and eventually new factions came into existence and reshaped the political landscape.

As a further development, quality management started off as production efficiency initiatives with F. Taylor mastered the decomposition of work modules in order to optimize them with training and efficiency training [8]. Then quality improvement concepts were introduced and the minimization of the number of production errors and waste was the primary focus [9].

Eventually, lean (management) principles evolved and represent the majority of quality initiatives in modern manufacturing initiatives [10]. Lean management can be described as rather an organisational framework than a production method.

Figure 4, Gross domestic product (GDP) per capita (2019) [11]

Basically, all steps along a production (process, activities etc.) are analysed, and unnecessary and overloaded steps are eliminated. Rigid and uncompromising quality management with fully documented processes is an essential part of modern manufacturing.

Reserves in stock, processing times and resource utilization rates are critically analysed. Redundancies and slack of any kind are reduced to a minimum or even eliminated. In particular, the reduction of stock has been an essential and very successful concept. In manufacturing this is mostly attributable to the improvements made possible by world-wide supply chain optimization. However, it has to be stated that the reduction of intermediate stock sometimes is implemented by shifting the burden from the producers to the suppliers. When looking at the complete production chain, the effects may remain limited.

The increase of productivity coming from the industrial revolution was seconded by the development of the free trade. World War II left Europe and

the rest of the world in destruction and disarray. Nevertheless, within 15-20 years the economies of most countries were re-established, and production levels were increased. Demand for industrial and consumer goods was tremendous. The war destroyed almost all of the infrastructure and consumers demanded more and more goods. First, for basic needs, then after saturation the consumer market evolved.

World-wide, the general wealth steadily increased, not only in Europe and North America, but also step by step in other regions of the world (see Figure 4 earlier). In the 1950s, after World War II and with the beginning of the re-establishment of world-wide transportation and financial services (banks and insurances) the industrial manufacturing principles developed to almost perfection. Many of these systems were already in place before. However, international treaties increased efficiency and scope. For example, the GATT (General Agreement on Tariffs and Trade, predecessor of the World-Trade Organization [12]) helped to establish trading channels and eased cross-country boundaries by reducing the burden of tariffs. Initially covering Europe and the Americas as member states, the organization evolved into the WTO and expanded into an organization of now 164 member states [13].

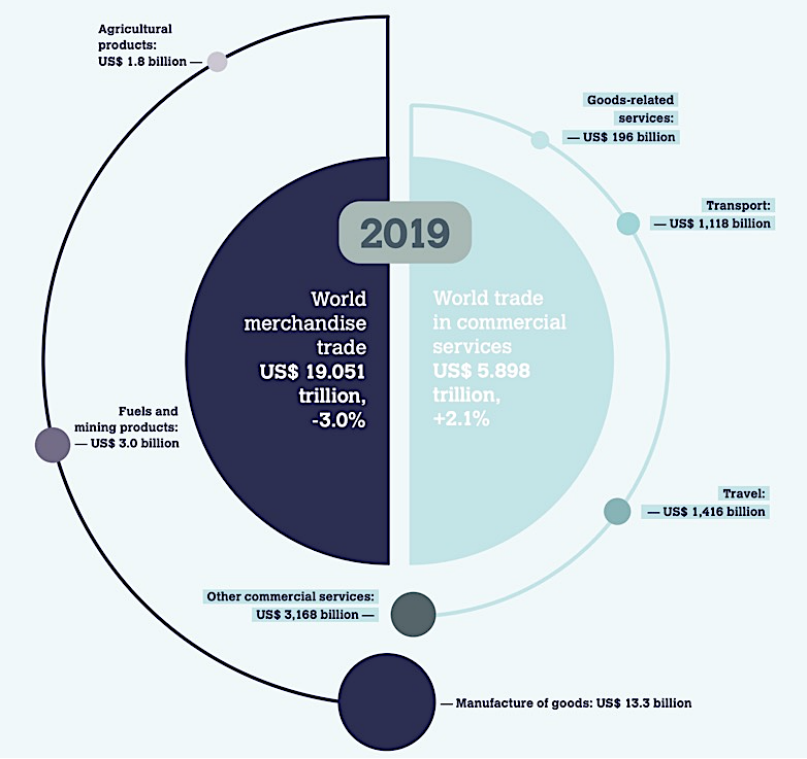

Figure 5, World trade volume 2019 [14]

The EGKS (Europäische Gemeinschaft für Kohle und Gas) established in order to control coal, gas and steel manufacturing across borders was established in 1951 and evolved to the European Union (before European

Economic Community), covering 27 European member states with 450m citizens up to current date [15]. The Regional Comprehensive Economic Partnership Agreement (RCEP, [16]) is the latest and largest initiative which combines the countries in Asia to form a free trade organisation with the focus on the exchange of goods and service. RCEP includes approximately 3,0 billion people and represents a union of the most dynamic economies of the planet.

Advances in availability and performance of international logistics and transport have added to the effect. Manufacturing became even more dislocated and flexible over the last years. Supply chains have been optimized up to a state that world trade and the exchange of goods grew exponentially. Figure 5 shows the situation as of 2019 where world trade (exchange of goods and services) reached a total of USD 19,0 billion and the exchange of services (travel, services, transport) came to about USD 6,0 billion, goods manufactured were about USD 13,3 billion.

All these efforts resulted in the world-wide manufacturing network that has been growing particularly in the past 20 years.

In the next chapter modern manufacturing concepts that were the enablers of the growing economy and wealth in the 20th and 21st century is presented.

2.3 Modern manufacturing

Production and manufacturing in the 19th century are based on production units that were able to make the complete set of supplies and assemblies that are necessary for the production of a particular good, mostly on a single production site. This included even the internal production of production equipment. The supplier market for assemblies was not yet developed enough, even though raw materials were purchased from outside sources. Producers had to take this into consideration and provide for everything themselves. Early car manufacturers had to be able to produce all of the materials and assemblies, from screws and washers to car tires. As a consequence, these production and assembly steps had to be concentrated at the same site, or efficient transport systems had to be in place. It resulted in huge factory complexes at a single site. In addition, the organisations along the supply chain were owned and controlled by one company. This principle is known as vertical integration, producing, controlling and owning everything within the production chain in one hand and at the same location. With the degree of specialization and a more diversified production the supplier skills as well as the market started to evolve. Production steps and assembly started to be more and more separated and decentralized. Distributed manufacturing then evolved and developed. The enterprises

started to develop decentralized production facilities that were coordinated centrally. Soon the distribution also meant that the value chain is no more completely owned and covered by the enterprise. Suppliers and supply chains evolved. The enterprises started to focus and concentrate on their capabilities and core competencies, leaving downstream activities out of the focus. These activities then became the business model others as their own core competences and activities. As a result, it created a supplier chain of enterprises, each of them concentrating on their own abilities.

The separation of the production process into supply chains allows each member of the chain to separately produce, transport and assemble semi-finished or finished goods. Each supply chain member can thus concentrate on his strengths needed to fulfil the (smaller) tasks instead of concentrating on the topmost of the product. Consider the production of a personal computer (PC). Production cost for labour intensive (assembly) tasks might be lower in one place than the other. Also, the availability and pricing of resources (e.g. rare earth metals) varies among countries or regions. Sometimes, the production near the customer site might be more beneficial in case of high transport cost or tariffs or import restrictions. This is specially the case when countries raise tariffs based on the assembly completion of the goods. Local assembly adding to the local gross domestic product (GDP) is treated favourably. These tariff schemes are common established with developing countries, though conflicting with most of the WTO targets. The following section will focus more on the manufacturing process.

Simply put, manufacturing is using production factors for the production of goods. These production factors can be elementary such as workforce, equipment or material or dispositive (controlling) such as management, planning, organisational [17]. Below a focus is presented on these factors and how they are affected by the current circumstances in later sections.

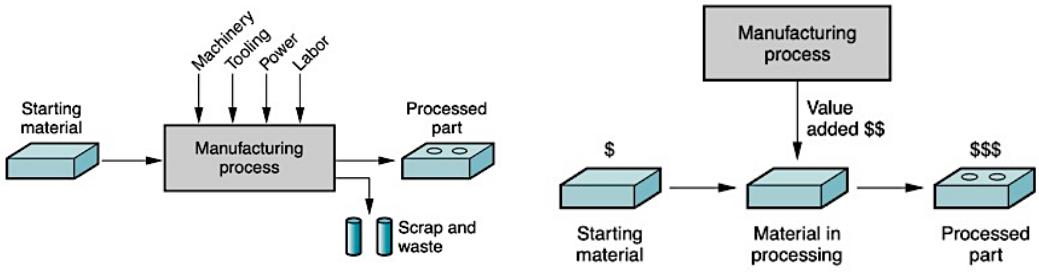

Figure 6, Manufacturing process (transformation view, business view) [18, p. 4]

From the processing point of view, manufacturing is commonly defined along multiple perspectives. The technical definition includes the processing of material from a source material to a finished product. Figure 6 shows the

general transformation view and the business view of the manufacturing process. In the transformation view a set of starting materials is transformed into processed part. The main issue here is the physical (or chemical) transformation of the starting materials by the means of machinery, tooling, power, and labour.

In addition to the output of processed parts (also half-finished or semi-finished parts) and/or finished products, the process is also producing waste material, and scrap.

The business view of the manufacturing process starts off with (various) starting materials (and their values), these materials are then processed through addition of machine or workforce labour, the result is a processed (or finished) part. The focus hereby is the value chain and the steps of adding value in order to achieve a surplus in monetary value. Clearly, this view is focussing on cost elements, costing, cost flow etc. – it represents the business view of the company.

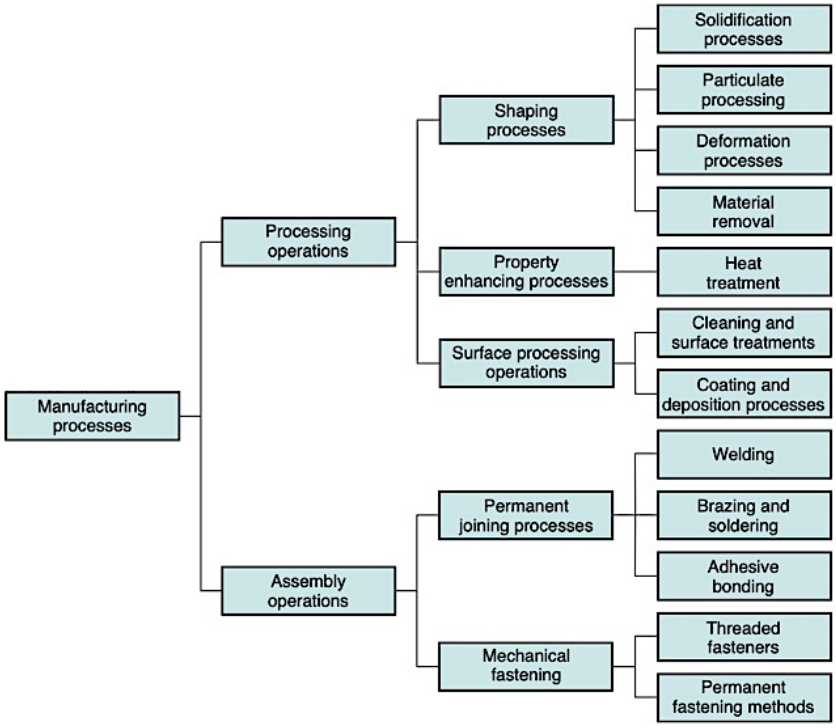

Figure 7, Manufacturing operations [18, p. 11]

The most common technical processes are depicted below in Figure 7. The main distinction hereby is the separation of the processes into processing operations and assembly operations. Processing operations transform a processed part from one state to another by using technical processes (physical or chemical) such as shaping, property enhancement or surface

processing. Assembly operations join two or more parts with either mechanical fastening (e.g. bolts) or permanent joining processes (e.g. welding).

2.4 Distributed manufacturing (DM)

Today, the manufacturing processes are organized centrally or distributed. Distributed manufacturing (DM) is understood as the technology, systems and strategies that organize the manufacturing with regards to location and scale [19]. This includes decisions on how to set up and scale the organization of the manufacturing process in different locations. As intermediate steps, finished or half-finished products (components) can then be brought together in further location where they are further processed and assembled. This introduces a key element to distributed manufacturing. DM therefore requires a highly sophisticated logistics system in order to bring the required assemblies together at the right time, in the right place with the required quality and the needed quantity. The logistics function then extends further to the customers locations for marketing and sales [20].

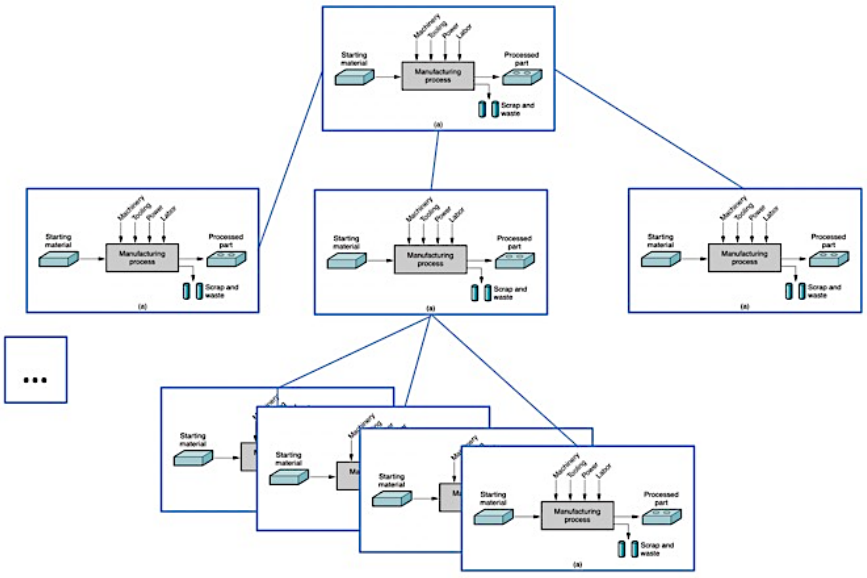

Figure 8, Distributed Manufacturing, relations (by author), based on Figure 6

Figure 8 depicts the inter-relationship of multiple distributed manufacturing sites. Basically, each of them can function as independent production units. However, in order to exercise control these manufacturing centres (or suppliers) are grouped into so called 'tier level system', mostly hierarchically. Car manufacturers have perfected the tier system for their production and achieved tremendous results in terms of quality and output volumes, but also commercially. In each tier level is responsible of a particular assembly or module, which then in turn require and receive input from other

manufacturers. Business relationships are established through supply contracts as well as service and production level agreements. Further determining factors for the success of this kind of setup are the supply chain and the data interoperability. The supply chain allows and ensures the availability of material and half-finished goods, between tier levels but also between the main unit and the customer. In this process, interoperability is of the essence. IT systems covering documentation, production planning, costing as well as sales and distribution functions are the prerequisite of this approach. Some details will be expanded below.

2.5 Advanced manufacturing, Industry 4.0

We mentioned earlier that centralized manufacturing includes the central control of the processes and the related data. In the early days of modern manufacturing, these processes were mostly located at the same site and it was easier to achieve coordination and the consistency of data, even though the majority of information was only available in analogue form (design drawings, descriptions, charts, work instructions). With the rise and stepwise introduction of modern digital data processing systems in the early 1960s this obstacle could be circumvented, and distribution was easier to achieve. The first applications were Computer Aided Design (CAD), planning tools, and simple database systems for storing information.

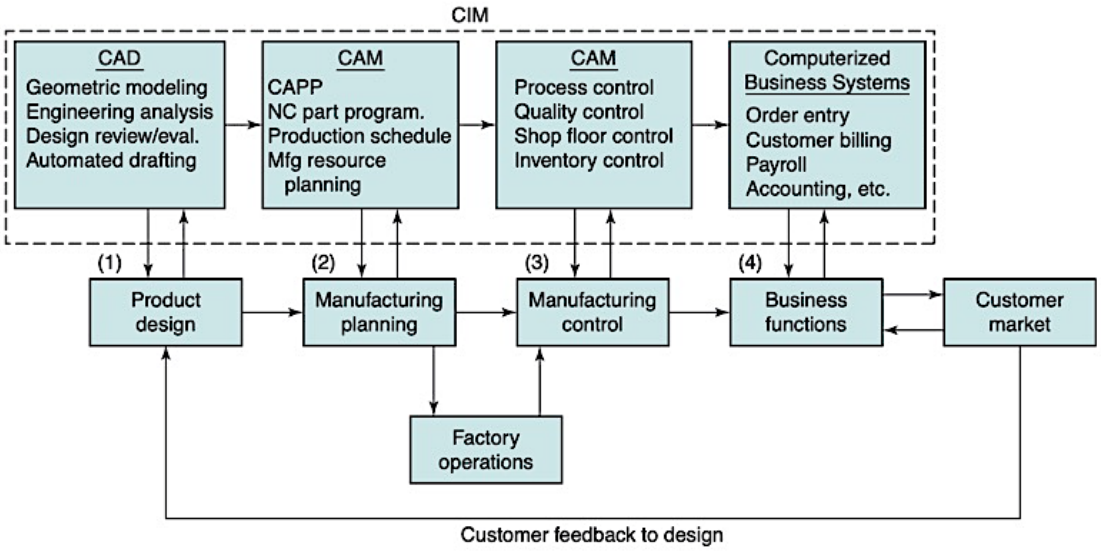

Figure 9, CIM functions [18, p. 940]

These early data processing systems were heavily centralized as well, due to technological reasons. With the emergence of novel system architectures, it became possible to distribute data processing on a large scale. The decentralization of the actual workspaces and locations where the manufacturing was performed. In parallel, the integration of data into the

information systems continued. Common databases and a higher level of data consistency was achieved.

Figure 9 shows the general functions in a manufacturing organisation. Computer Integrated Manufacturing (CIM) summarizes these functions and describes the organizational integration thereof: Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) with scheduling and process control (PC) as well as the business functions such as billing, costing with the respective interfaces into the accounting and sales management functions.

All of these functions in manufacturing, manufacturing control, planning, design as well as in administration and sales generate a considerable amount of data. This data can be of various data types and purpose. Drawings, bill of materials, production plans, work instructions are related to the actual manufacturing process and are complex and highly interrelated. In addition, manufacturing also generates a lot of required data for pre- and post-manufacturing phases such as quality documents, costing information, billing data, and customer related data. All these data have to be stored, processed and sometimes integrated into upstream systems as well [21, 22].

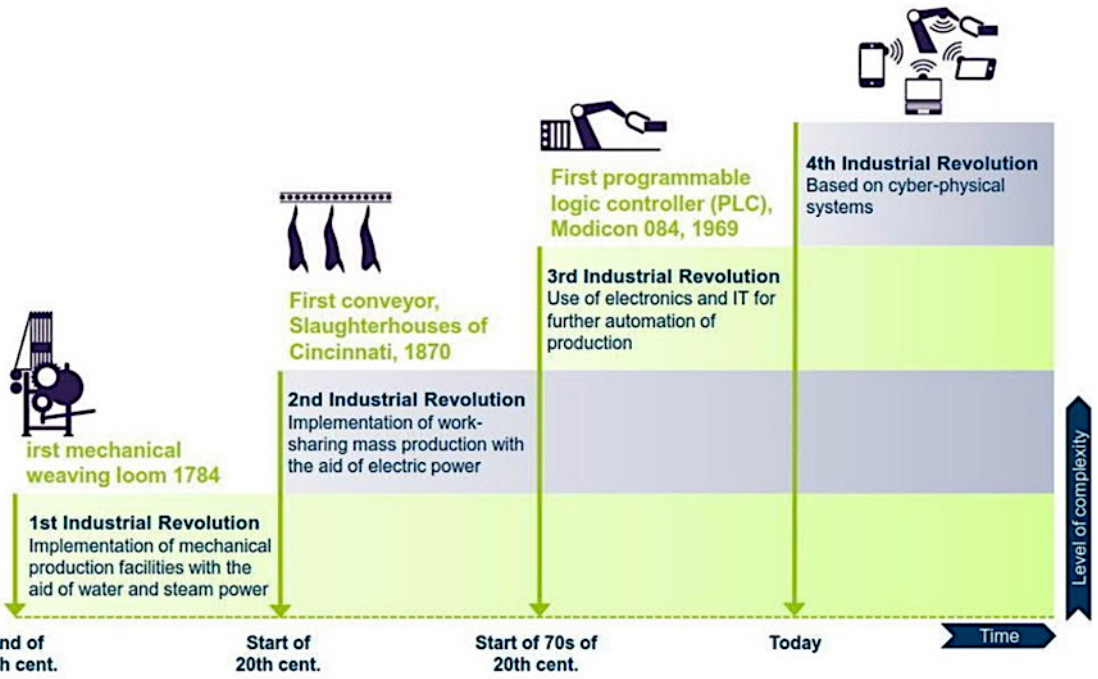

Figure 10, from Industry 1.0 to 4.0 [23]

Industry 4.0 represents the latest development in manufacturing and can described as 'the intelligent networking of machines and processes for industry with the help of information and communication technology' [24].

Figure 10 shows the time relationship between industrialization in the 18th century until the recent development in the 21st century.
The 'Plattform-Industrie 4.0' describes the main functions as (quoted from [24]):

- 'Flexible production: In manufacturing a product, many companies are involved in a step-by-step process to develop a product. In being digitally networked, these steps can be better coordinated, and the machine load better planned.
- Convertible factory: Future production lines can be built in modules and be quickly assembled for tasks. Productivity and efficiency would be improved; individualized products can be produced in small quantities at affordable prices.
- Customer-oriented solutions: Consumers and producers will move closer together. The customers themselves could design products according to their wishes—for example, sneakers designed and tailored to the customer's unique foot shape. At the same time, smart products that are already being delivered and in use can send data to the manufacturer. With this usage data, the manufacturer can improve his or her products and offer the customer novel services.
- Optimised logistics: Algorithms can calculate ideal delivery routes; machines independently report when they need new material—smart networking enables an optimal flow of goods.
- Use of data: Data on the production process and the condition of a product will be combined and analysed. Data analysis provides guidance on how to make a product more efficiently. More importantly, it's the foundation for completely new business models and services. For example, lift manufacturers can offer their customers 'predictive maintenance': elevators equipped with sensors that continuously send data about their condition. Product wear would be detected and corrected before it leads to an elevator system failure.
- Resource-efficient circular economy: The entire life cycle of a product can be considered with the support of data. The design phase would already be able to determine which materials can be recycled.'

Additional definitions for Industry 4.0 are available and plenty. However, a most striking one may best describe the concept: *Lot size 1* is one of them and it focusses on the maximum flexibility on the manufacturing process, given small production numbers and the high variability in the product features.

It combines the customer orientation mentioned above with the flexible manufacturing feature. Whereas earlier production concepts focussed on the mass production of goods, novel concepts concentrate on flexible production of customer designed product options, even though the latter is rather a limitation of product options presented than a real customer design available. The production of capital investment goods is in any case customer tailored rather than mass market. Large machinery and equipment have mostly been customer designed.

Another is descriptive term of Industry 4.0 is the notion of *Internet of Things (IoT)* which denotes the concept that all real-world items are transparently available and accessible through the internet protocol.

It has to be pointed out that Industry 4.0 is not an available product or a marketable commercially available system. Rather Industry 4.0 must be an evolving concept and can be considered rather the next development step from automated systems (aka Industry 3.0, CIM) towards smarter and (more) flexible manufacturing and internet of things (IoT) concepts.

Further technologies such as artificial intelligence (AI), robotics and 5G[1] are drives and prerequisite of the next steps alike. Further adaptions due to technical advances are certain to be promoted in the upcoming years.

2.6 Risks & opportunities

Distributed manufacturing and world-wide trade have many advantages and considerably increased wealth in all over the world. However, the benefits also come with trade-offs and an increase of risks. In this thesis, we are looking at special events with disruptive characteristics. Events that are going beyond the routine coverage mentioned above are called disruptive events. Examples for disruptive events are natural disasters such as volcano eruptions, tsunamis, or man-made disruptions that hinder the development of a region (man caused environmental catastrophes, war) or even the world. We are currently facing such a disruptive event in form of an infectious disease outbreak. Below one of these special risks is further on presented.

The imminent COVID-19 pandemic in 2020 (see *The COVID-19* pandemic*)* represents this disruptive element and uncovers the risks that are involved when dealing with it. This is not only attributable to the economic

[1] 5G as the successor of LTE (long term evolution) is focusing on IoT (internet of things), large bandwidths (10 Gbps) and ultra-short latency (1 ms). However, at this time only few implementations are available, primarily focusing on the enhanced mobile bandwidth (eMBB) feature for higher bandwidths [46].

development, but also has effects on the general wellbeing of the population. In the following chapter the thesis is focussing on the consequences on distributed manufacturing. However, first an introduction of pandemics and try to position the current COVID-19 pandemic into the history of pandemics is given. Then follows an overview of the development of distributed manufacturing and describe how the pandemic drives novel approaches and new developments in management and manufacturing.

3. Pandemic conditions

In this chapter an overview of the definition of pandemic conditions is presented. This will be followed by a brief historical overview on pandemics and describe the most noticeable cases and events with the focus on the 20th and 21st century. COVID-19 will be described in more detail. The current state of dealing with this epidemiolocal pandemic and the consequences on everyday life and business will be discussed.

3.1 What constitutes a pandemic?

Epidemiology and virology define a pandemic as an 'epidemic occurring worldwide, or over a very wide area, crossing international boundaries and usually affecting a large number of people' [25]. The focus of this definition emphasises the geographical aspect including a world-wide and cross-continent dissemination of a disease. Further definitions focus on a wider range of aspects, such as reoccurrence, population immunity, transmissibility, disease severity and others. For this purpose, the paper uses and focusses on the former definition.

NEW PHASES	OVERARCHING PUBLIC HEALTH GOALS
Interpandemic period	
Phase 1. No new influenza virus subtypes have been detected in humans. An influenza virus subtype that has caused human infection may be present in animals. If present in animals, the risk[a] of human infection or disease is considered to be low.	Strengthen influenza pandemic preparedness at the global, regional, national and subnational levels.
Phase 2. No new influenza virus subtypes have been detected in humans. However, a circulating animal influenza virus subtype poses a substantial risk[a] of human disease.	Minimize the risk of transmission to humans; detect and report such transmission rapidly if it occurs.
Pandemic alert period	
Phase 3. Human infection(s) with a new subtype, but no human-to-human spread, or at most rare instances of spread to a close contact.[b]	Ensure rapid characterization of the new virus subtype and early detection, notification and response to additional cases.
Phase 4. Small cluster(s) with limited human-to-human transmission but spread is highly localized, suggesting that the virus is not well adapted to humans.[b]	Contain the new virus within limited foci or delay spread to gain time to implement preparedness measures, including vaccine development.
Phase 5. Larger cluster(s) but human-to-human spread still localized, suggesting that the virus is becoming increasingly better adapted to humans, but may not yet be fully transmissible (substantial pandemic risk).	Maximize efforts to contain or delay spread, to possibly avert a pandemic, and to gain time to implement pandemic response measures.
Pandemic period	
Phase 6. Pandemic: increased and sustained transmission in general population.[b]	Minimize the impact of the pandemic.

Figure 11, Pandemic periods [26], [27]

The WHO [26] extends and details the basic definition and adds the above-mentioned phases in the definition (Figure 11). The occurrence of a new

disease is measured in phases, which is basically related to the outbreak cycle of any disease – inter-pandemic period, pandemic alert period, and pandemic period. The earlier phase of 'interpandemic period' describes a situation between pandemics where no new (influenza) viruses are known, and no new subtypes are discovered. In the 'pandemic alert period' new infections (or viruses) are detected. The number of transmissions is still low, and the way of transmission is limited. The severity and transmission speed as well as the number of cases increase with the phases. The 'pandemic period' (= phase 6) then defines the occurrence of a pandemic as 'increased and sustained transmission in the general population'. Disease and transmission are at the highest levels. We have to be aware that this is not a static and limited process, it is cyclical and ongoing on various (virus)levels. At any point in time there are multiple diseases (viral or bacterial) in various phases, transferring from one phase to the other, or disappearing. It is a constantly evolving multi-populated cycle of developments.

3.2 A historical view

Over the centuries, many examples of pandemic outbreaks are available. Mostly these pandemics are related to plague, cholera, typhus, measles, tuberculosis, malaria typhus, smallpox, HIV, and influenza, with potentially new diseases evolving. From today's point of view and given the definitions mentioned above, a lot of the earlier pandemic events in history are locally related and thus would therefore not be included in the current definition. However, the eradication of cities and regions in earlier history still represents a considerable event, under all aspects and considerations and therefore it is worth mentioning. In addition, general population numbers and population densities were smaller at that time.

Over centuries the bubonic plague (bacterial infection) was taking its toll all over Europe and Asia. The bubonic plague, also known as black death, spread by infected fleas and has a death rate of up to 90 % among the infected targets. An estimated 50 million deaths occurred when it swept across Europe in 14th and 15th century. Given the smaller populations at that time, this represents a tremendous toll, which related in about 50 % of the European population at that time. Up to now, no vaccination could be found against this disease. Though, antibiotics have proven an effective treatment and applied successfully over the past 50 years. The disease has never been eradicated, which is partly due to the bacteriological origin of the disease. Probably, the main reason for the reduction of cases is due to improved hygienic conditions that took place in the late 19th century, mainly when dealing with dead corpses and cadavers [28].

Smallpox (variola virus infection) kept on taking its toll in the overall population over centuries. Estimates are that smallpox was responsible for 300-500 million deaths over the last centuries. From the late 1950s to the late 1970s the World Health Organisation (WHO) conducted and advocated a world-wide vaccination campaign which resulted in the eradication of the smallpox disease [29], [30]. To this day, the smallpox virus is eradicated, and vaccinations are no more performed, however the vaccine is still available for emergency cases. The eradication of smallpox certainly represents a huge success in the fight against pandemic diseases. Smallpox represents a rare exception in so far that after the discovery of a vaccination in the 18th century the disease has been eradicated (so far).

HIV (human immunodeficiency viruses) are blood-transmitted viruses and emerged in the 1980s. The virus is believed to originate from non-human primates, notably African chimpanzees and mangabeys. The virus effects the immune system and leads to the progressive failure of the immune system (AIDS). Treatment is based on anti-viral cocktails. The life expectancy after infection thus evolved from 3-6 months in the early 1980s to 20+ years (as of 2020). The research for a vaccine is ongoing but given the retroviral characteristics of the virus stem success has not yet been reached. As of 2019, the WHO estimates about 38m infected people world-wide [31].

Influenza (virus infection), not to be confused with the much less dangerous but still highly infectious cousin 'common cold', is a viral infection that causes serious symptoms with a mortality rate of 10-15 % when left untreated. A special characteristic of the influenza viruses is the fact that they will evolve over time and multiple stems and strains are known. The ability to constantly evolve and mutate leads to new viruses and new influenza epidemics on a regular basis. Up to now this problem has hindered the development of a general vaccine. Vaccines for special mutations are available, however a general influenza vaccine is out of reach, leaving pandemic research one step behind. Typically, given the seasonal cycles the influenza occurs twice per year. The cold season favours transmission conditions [32].

Influenza epidemics are known for centuries. Most notably, the Spanish flu (H1N1 virus), although originally spreading from an army hospital in the US, has to be mentioned. From 1918-20 it spread over the US and Europe and lead to an estimated 500 million infections and 17-50 million deaths. The pandemic occurred in the last period of World War I and therefore the numbers reported were heavily influenced by statistical blur and censored reporting. Even though, it is known as the biggest influenza pandemic until now.

In 2002 an up to then unknown type of virus emerged. SARS (severe acute respiratory syndrome) first appeared in China (Foshan, Guangdong). The virus spread across Asia and left about 800 deaths. In 2012, the middle east respiratory syndrome (MERS) soon developed. The origins were bats and camels, the disease led to about 2.500 deaths, with a mortality of about 35%. A vaccine is currently unavailable.

The emergence of the corona virus family (SARS-CoV-1 and -2, MERS-CoV) lead to an increase in research of animal to human transmissions (zoonosis). These viruses infect animals, and these animals can spread the disease across species, up to human species. Given the higher population densities and regional food preferences the animal to human spread of diseases became more likely and more common. Dog-, avian-, swine-, horse- and cat-flu are examples of such transmissions. The most common one war the Asian flu which lead to a pandemic in 1957, leading to an estimated 2 million deaths globally.

3.3 Economic consequences of pandemics

The pandemics mentioned above were all having consequences in various developmental aspects of societies. The aspects influenced the general public, had medical impact on research and treatment options but also economical influences. For the aspect of manufacturing, the bubonic plague had a tremendous impact, but rather a positive one. It can be considered as one of the main drivers of the industrialization on the European continent. Though 200 years earlier than the industrial revolution, the de-population of the cities, counties and therefore all economic domains had severe economic consequences. Simply put, workforce was in very high demand and implied all aspects of work. Naturally, agriculture as the main employer of workforce was affected instantly. Not only workforce was scarce but also relationships between farmers and landlord changed to more favourable agreements for the farmers, nobility though still had the upper hand.

Competition for the workforce also increased salaries and thus the need for technical rationalization, even though it took 200 years and many other aspects to initiate the technological revolutions of the 19th and 20th century [33]. Earliest examples of technical innovations and inventions such as the early piston machine (Huygens, 1680), calculation machine (Pascal, 1642), printing press (Gutenberg, 1439) show first signs of the industrial development that shaped the 19th and 20th century.

The influence of the smallpox pandemic on manufacturing operations was particularly focussing on the pharmaceutical industry. The program for

eradication advocated by the WHO [29] was very ambitious and successful. It led to the development of a cost-effective needle and novel production processes for large scale vaccine production [30]. The vaccination campaigns required an 80%+ coverage, requiring about 3 billion doses throughout a period from 1966 to 1977. Let us keep this time frame in mind when following the public discussions about the vaccination programs for the current COVID-19 pandemic.

SARS and MERS impacted manufacturing considerably due to the lockdown measures that were taken in the 2010s in the fight against the diseases. The effects were similar to the consequences that we are facing under the current conditions. However, the impact was minor compared to the latest developments. COVID-19 will be presented in the following chapters.

3.4 The COVID-19 pandemic

COVID-19 is an infectious disease caused by the SARS-COV-2 virus (severe acute respiratory syndrome coronavirus 2). It stems from the corona virus family. The virus was first identified in December 2019 in Wuhan (China). The virus is transmitted via aerosols, respiratory droplets and body contact and quickly spread across the world. The WHO announced COVID-19 outbreak as a pandemic on 11 March 2020, about 3 months after the first cases were reported.

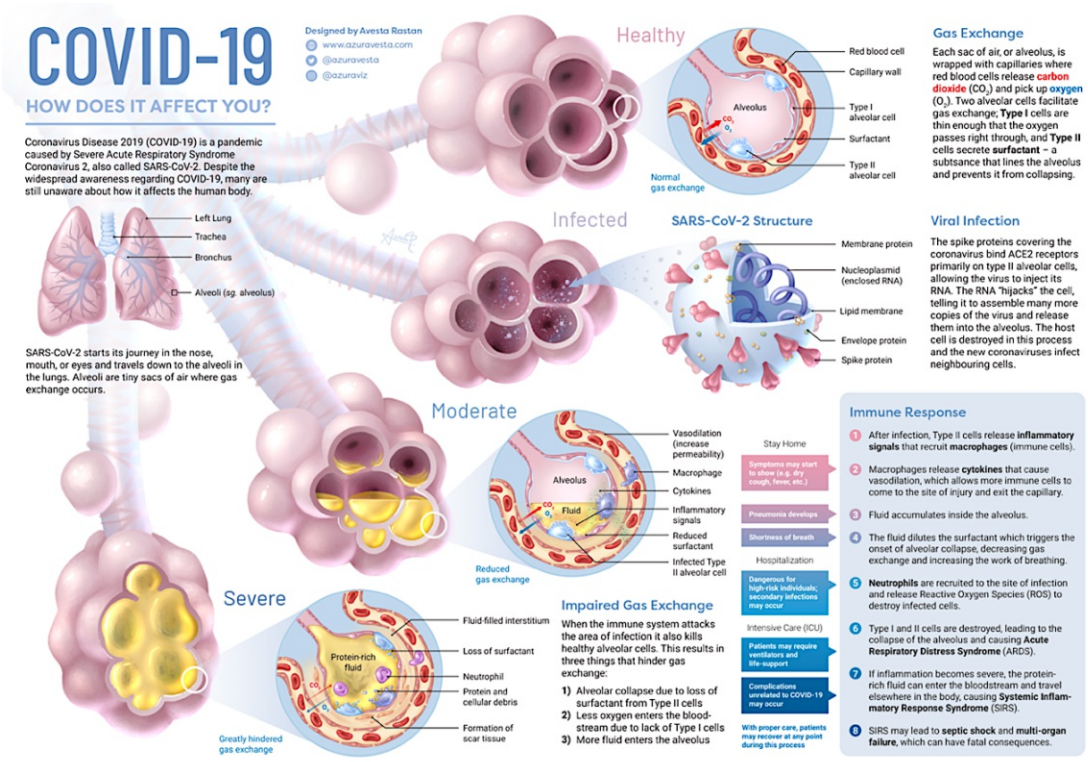

Figure 12, COVID-19 viral effects [34]

The virus name COVID-19 'CO' stands for corona (virus type), 'VI' for virus and 'D' for disease, '-19' stands for the year when the novel strain was discovered. Earlier the virus was called SARS-CoV-2 named by the International Committee on Taxonomy of Viruses (ICTV) [35].

Previously, the name of the virus was referred to as '2019 novel corona virus'. Also here the numbering '19' refers to the year when the virus was discovered, rather than a version or sequence number.

As of March 2021, we see a reported number of about 113,8 million cases worldwide[2], the number of non-reported cases is obviously unknown. The number is heavily dependent on the number of tests that are available in a region or country. The number of deaths is currently reported with 2.527.000 cases world-wide [1]. Though some of the countries report a flattening curve of the infections, there is currently no clear view on when the pandemic will be over or contained.

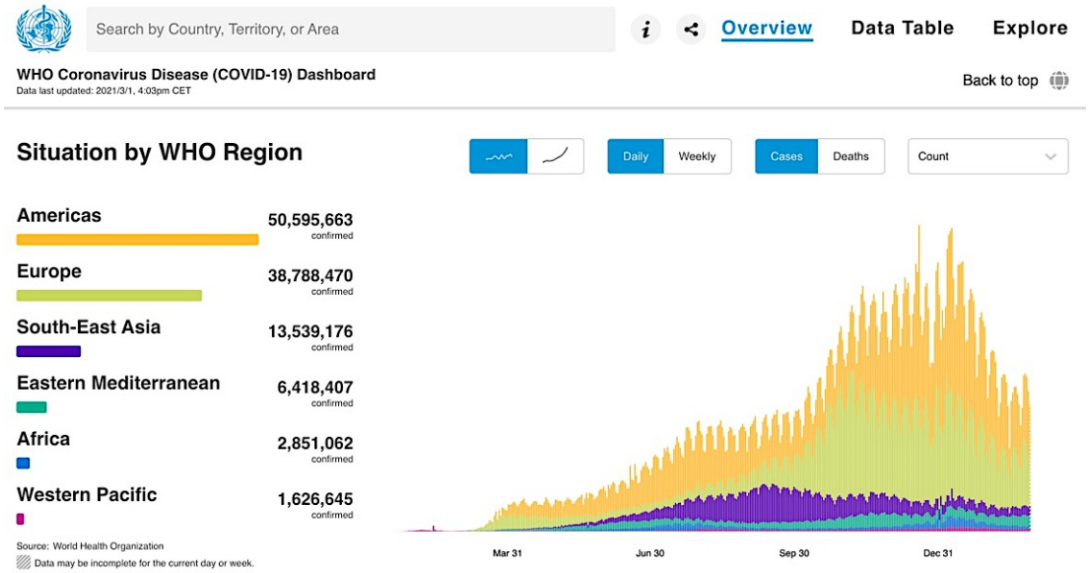

Figure 13, COVID-19 global cases [1]

Figure 12 depicts on how the virus attacks the human body and how the respiratory disease evolves. Symptoms of the disease vary, but all affect the respiratory function of the body. Mild cases show no or common cold symptoms. More severe cases lead to a complete respiratory failure with the

[2] The number of infections, death and other statistical data change on a daily basis as this work develops. The current actual development of the disease with number of cases along multiple dimensions such as countries, developments and further metrics such as death rates can be found various websites (WHO COVID-19 dashboard [49]).

need of ventilators. Elderly people with respiratory disease history are more in danger than others.

Figure 13 depicts the current COVID-19 infection situation based on the regions of the world [1], further sources and statistics are available. It visualizes the distribution of total infection cases in the world regions. This figure shows that, after almost one year after the first outbreaks were detected, the virus outbreak has reached full pandemic conditions (Figure 11, phase 6). Basically, the whole world is concerned, the number of cases differs due to different stages of the infection progression as well as disease control policies.

Currently, the main effort for limiting the disease is to restrict the spread of the infections. This corresponds with the 'phase 6' of the pandemic phases mentioned earlier. The overall public health goal is to minimize the impact of the pandemic. This can be done by fairly easy methods. Maintaining physical distance, hand washing and avoiding people. Easy in terms of that there is no technical effort needed to set the methods in place, no medicine, apparatus is required. It can be achieved by organizational efforts. Certainly, organizational matters require strength and determination to be put in place.

Efforts for developing a vaccine are ongoing. A never-before number of research institutions equipped with increased research funding and considerable support are working on the development of vaccines. Clinical trials have just begun.

We have to be realistic at this stage. Vaccine development usually goes through an

- exploration stage, followed by
- pre-clinical and clinical stages. After that a
- regulatory review follows. After approval the
- manufacturing takes place.

Only then large-scale or global vaccinations can be put in place. Quality control in subsequent periods is necessary and required. For the COVID-19 vaccination development we are now for early research programs in the clinical development stage. Even though all the phases are tightened as much as possible, the quality control and regulatory aspect of developing the vaccination must be taken with caution. Only then the manufacturing can be put in place. Producing and distributing 7 billion doses of a vaccine is a demanding task and will take its time and effort, even though a tremendous public requirement will back the process. However, this is the best-case scenario. We could also face the situation where vaccine development is not as successful as hoped. Either no vaccination at all (HIV) or a booster

vaccination that protect a limited time period (influenza) could be the result as well.

The latest developments forecast the broad availability of vaccines in the 2nd quarter of 2021. As of March 2021 several vaccines are already authorized and available on the European market (Comirnaty by BioNtech/Pfitzer, COVID-19 vaccine by Astra Zeneca, COVID-19 vaccine by Moderna) [36] and the production of the vaccine is scaling up in order to satisfy the tremendous demand.

Tests for COVID-19 are available and give results within hours after testing. However, testing capacities and availability vary from country to country.

Given the relatively long incubation time of about two weeks the disease remains undetected for some time. As an immediate reaction, countries initiated a lockdown on a regional basis (city, region, counties) which resulted in a decrease of new cases and a slowdown of the spread. Some countries restrict inbound and outbound travelling, some on the basis of virus test certificates. Holiday destinations worldwide suffer a decline in numbers.

The economic and social life is currently limited or came to an end or at least was severely reduced. Economic indicators [37] show a reduction of the economic output, -15 (Germany, Source), -35% (US, source) and -7 % (China).

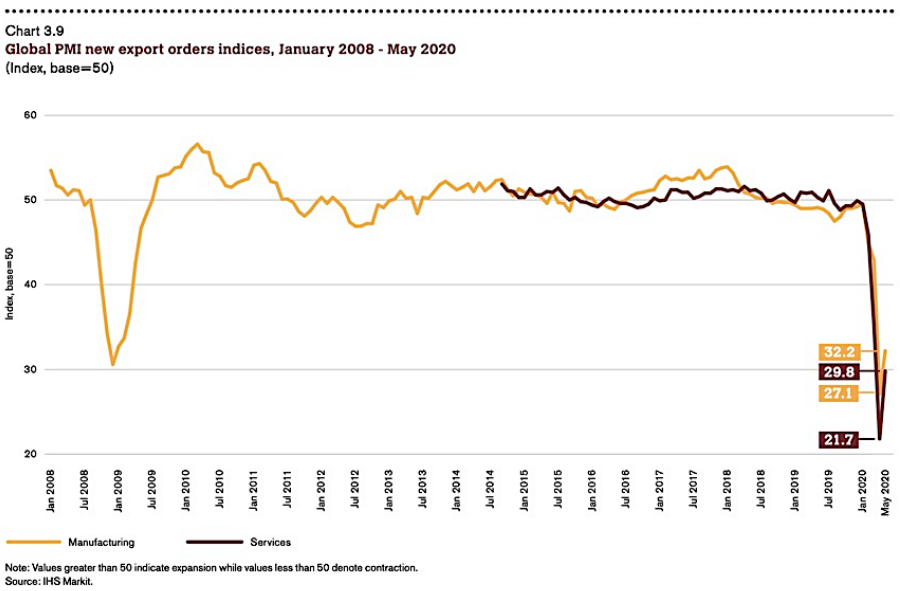

Figure 14, Reduction of export business [38]

On a global perspective the WTO Statistical review 2020 depicts this sharp reduction of the export order index. However, it also shows a steep incline after the first recoveries after their 1st waves. Unfortunately, further waves will

have similar effects, a clear and sharp V-shape effect is certainly desired but might not materialize accordingly.

Effects depend on region and infection levels but also on industries. Cruise shipping and airlines came to an almost complete halt, while other sectors benefited from the circumstances of physical distancing such as web shops (e.g. amazon) and online entertainment (Netflix e.g.) but also an increase in the usage of modern video conferencing tool (e.g. Zoom).

3.5 General consequences of COVID-19

When compared to previous pandemics the epidemiological principles did not change and apply as well. However, there are some differences that need to be taken into consideration when looking at the current pandemic situation.

- World-population with currently 7,8 billion people (2020) [39] on an absolute level is as high as never before. Population densities have increased constantly, some areas reach up to 10.000 people per km^2 (with some areas go up to 30.000) This limits physical distancing efforts. A lack of self-discipline adds to the problem.
- Mobility in the 21st century is as high as never before. The exchange of ideas, people, goods between countries, regions and continents has risen to a level never observed before. Many countries have preferential treatment of people and goods transfer, e.g. the European union with its common market scheme, but also the WTO treaty with a focus on free trade and the flow of goods and capital. World-trade went up 3.000 % from post-war 1950s to current levels.
- Globalization has taken then both economic and social live to a never before interwoven and interrelated level. Relationships and ties are omnipresent. Previous centuries and generations have been much more local in their organizations and effects. This certainly applies to businesses and thereby particularly to manufacturing organizations.

When comparing COVID-19 to the SARS/MERS epidemic in the early 2000s we see a great difference in some of the direct consequences. Whereas SARS mostly had a limiting effect on the mobility of people, COVID-19 is also restrictive on the mobility of goods. This is mainly due to the lockdown requirements, which are mostly implemented region by region. As a consequence, the transfer of people (and therefore goods, someone has to drive the truck/train) can therefore be limited or interrupted due to viral testing or general lockout schemes.

The consequences for social life, business and for companies are therefore tremendous:

- The disease is highly contagious. Therefore, home office is applied where possible. On site work is organized with distancing rules applied. Travel is almost impossible and in case limited to special destinations.
- Physical distancing measurement apps are common, but usage varies from country to country.
- Infection rates of COVD-19 are very high, given the current population densities (especially in the cities) this requires more distancing.
- Symptoms of the COVID-19 are clear and visible on a later stage of the disease. However, in early stages or mild cases they do not differ from common cold diseases, therefore the disease is more invisible than others.
- Treatment is limited to pulmonary support through ventilators and anti-viral drug treatment. Both, with restricted effectiveness and they come with considerable side-effects. This represents a snapshot with the current state of the art. Research (treatment and medication) and clinical programs are ongoing, hopefully with better and more efficient results.
- The overall 5-10% infection rate (generating anti-bodies) is still relatively low, given that herd-immunity can only be reached at a level of 60 % and more.
- Lockdowns, travel restrictions, health management issues and (business) restrictions on all levels are going to continue over the next years.

This chapter described the history of pandemics with the focus on recent unfortunate developments, notably the SARS/MERS/COVID-19 pandemic. The latter with a lot of open issues, problems and unresolved epidemiological treatments, such as physical distancing, lack of proper treatment and vaccine development in the early stage.

Clearly, this represents an extremely disruptive element in economic relations on a world-wide scale. The consequences are large scale. There are no alternatives than to address and to cope with these new circumstances and conditions.

The consequences and its effects on organisations, businesses and economic regions and a framework for working under pandemic conditions will be discussed in the following chapter. In particular, a special focus on distributed manufacturing in pandemic conditions will be presented in the next chapter.

4. Distributed manufacturing under pandemic conditions

In this chapter we turn our focus on the various challenges that management is facing when operating a business or company of any size. First, we look at a few more general decisions and challenges that managers are facing regarding organizational challenges. The problems, tasks and responsibility vary from case to case, depending on what business area, regional differences, product, environment, and legal system the businesses operate in. Variations in multiple sites when operating internationally might increase to the challenge. Then our focus turns to decision making in distributed manufacturing. Finally, operational suggestions and recommendations are presented on how to manage the challenges we are facing through the pandemic conditions we are currently going through. Various methods of risk mitigation will be presented. Several examples with possible solutions to some of the problems will be presented.

4.1 Management

Plenty definitions about management and the related tasks and responsibilities can be found and management paradigms are abundant [40]. However, on the operational level it always comes down to running and shaping organisations. Management can be defined as the task of setting up an administration, setting up targets, controlling and developing resources to fulfil the company targets [41]. Management is thus the general principle of modern companies. Management is a function on various levels within the organisation.

In general, the management defines and operates companies of any kind that can be described with the following main characteristics. These characteristics define how the organisation is built (structure), how its behaving (rules), the environment it is working in, the legal framework that it operates, the infrastructure as well as the related stakeholders (internal and external).

4.1.1 Company environment, legal framework, infrastructure

The company environment can be defined as the surrounding systems that define economic, legal and social conditions. Legal environment and infrastructure are among the most important environmental influences and their influences will be described below.

The legal framework represents a cornerstone of any company environment. This reflects the laws and regulations for businesses, employment, social and environmental standards as well as the cultural background. It extends to the legal system with the executive power as well as how the courts operate.

Hereby, it ensures that the legal framework can be executed and moreover that it is sustainable and reliable. The latter represents a one of the most important cornerstones of investor safety. Obviously, there are only limited ways for a company or organisation to influence these external conditions. However, interest groups and professional support and lobbying organisations allow for providing help and support to get a favourable impact of the company settings.

The infrastructure represents the facilities and their investments that companies require to perform adequately. Obviously, any business environment has different requirements when it comes to public infrastructure. Engineering companies might have a focus on educational and universities support, whereas production-oriented businesses rely on educated workforces as well. Commonly, any business nowadays relies on communication infra-structure, transport, and traffic infrastructure. The former to move information, the latter to move people and products. Finally, the finance industry (e.g. banks, insurances) ensures the free movement of money and the provision of capital needs as required. In addition, given the time and capital investment required, these are long term decisions that are not only costly when undergoing a change but also take considerable time in planning and implementation.

4.1.2 Organisational structure and behaviour

The organisational structure defines the framework of tasks, responsibilities, competences and operational knowledge an organisation is built of. This also includes competences and decision delegation between these units. The behavioural description of an organisation describes the way an organisation with all of the constituting members of departments, employees, and external partners is working together. There are multiple layers for consideration; behaviour within the organisation (i.e. a department, sub-departments), between the structural units (i.e. inter-departmental) or as an organisation with another organisation (i.e. inter-organisational), or environment.

This includes how decisions are made and how the communication flows between the units within the organisations[3]. Obviously, the organisational behaviour in not only defined with regard of the internal, but also regarding

[3] It is pointed out that not only formal decision and communication patterns define an organization. Informal communication and decisions making are known to be at least equally important. We refer to [47] for an analysis.

the external partners such as customers, suppliers (of different levels), service partners, governmental and non-governmental institutions.

Management challenges navigate through the framework, environment and stakeholders mentioned above. In the following those categories are shown that are in the focus of a distributed company in the manufacturing business.

4.2 Production factors

In previous sections we have shown the features of modern distributed manufacturing and described the general management tasks. In the following this thesis concentrates on the determining factors that relate to manufacturing organisations.

When looking at manufacturing organisations some differences to conventional organisations are evident. Manufacturing organisations deal with the production of real and tangible outcomes, the 'real' things. As a contrast to the new technologies, the product does neither form administration, nor services, nor intangible assets such as computer software and ideas. It is obviously targeting results with physical characteristics of the resulting outcome; 'things' are produced. However, in sometimes the services that are leading to a product can be marketed and sold themselves.

In the case of distributed manufacturing (DM), the production process is performed in different locations under special conditions and control. As the production deals with material outcomes, the handling, transport and storage requires special focus by the management as well.

Manufacturing management deals with the planning, scheduling and controlling of manufacturing processes. It guarantees the efficient layout of production, the smooth transport flow of material and the availability of the necessary workforce in the needed quality and required quantity. Further tasks and responsibilities are purchasing, operational safety and quality management. In operations respect this includes organizing the production means such as employees, products, material, equipment, and IT.

To be more specific, the following responsibilities, items, and issues need attention, when dealing with distributed manufacturing:

- People make up one of the main productivity elements in any organisations. A common distinction is made into administration staff and (factory floor) workforce. It is essential that staff is available and trained in order to be up to the task for running the manufacturing organisation. The group we cover here are made of administration staff, workforce, and all

other personnel on site, which might not necessarily be employees of the company. As in any categorization the groups may be interleaving.

- Products (or semi-finished products) are the tangible outcome of the manufacturing process. The process is for making the product is essential any manufacturing related issues. The technical design of the product determines the manufacturing process strongly. The data for the technical design are usually kept in product lifecycle management systems (PLM), covering all specifications, technical details, material specifications, standards, and above all coming in all kind of variants. This data will also include the localization of material data that stem from localized suppliers or simply if the material is only available at certain qualities in a particular region.
- Material, base or intermediate materials (assemblies) are the essential basis for any manufacturing process, availability and quality is of course essential to the outcomes. The availability of supplies sources locally plays into this to a great extent. Therefore building up suppliers in the local manufacturing site region is crucial for the success, any change in sourcing material provenance is also a question of a qualified supplier base.
- Equipment for the manufacturing is essential in order to produce an outcome. Equipment is related to the technical product design which in turn determines the design of the production site or factory. The latter is a long-long term issue given the time and capital expenditure it takes to set up a production site.
- Information technology (IT) is essential in 21st century manufacturing, the development depicted earlier shows this development. IT is covering all equipment, networking on site and between sites, and telecommunication; both for administration and for production facilities.
- Quality management (QM) is an essential tool for creating customer satisfaction, increasing efficiency and thus ensuring profitability. The quality management settings are mostly mandatory in all of the production sites, details may vary along the lines where material availability and client requirements are mandating adaptations.
- Partners are a resource and factor that appears obvious but often is not taken into consideration as a risk item. Firstly, communication has to be kept up with any related parties. It is essential and the information flow will help to setup the internal action plans. Secondly, the risk mitigation of the partners (e.g. material suppliers, service companies) might have profound effects on the action planned in the first place. It must be kept in mind that partners in this sense also include local service providers and related local government agencies.

When dealing with these production factors plenty of decisions have to be made under a multitude of conditions. These decisions come with risks and opportunities. Let us focus on the risks, for now.

Manufacturing represents a very complex and interwoven system and influencing factors are many. This is particularly the case the more distributed and the more complex systems evolve. The types of risks can be manyfold, some are described below:

- Markets move; Market and consumer requirements may shift over time. Not only can consumer market move or evolve (e.g. South East Asia, BRIC countries, China, US and EU developed to market countries) but also supplier markets can develop or shift (higher wages, resources no more available, or needed)
- People face travel restrictions, caused either by basic logistical problems (availability of flights), legal restriction (visa regulations) or health restrictions (quarantining).
- Required resources, not limited to materials or primary products can move and require additional focus, e.g. coal no more needed. Automation is also advancing in developing countries thus putting tension on whole regions (e.g. rare earth mining and availability).
- Research and development can shift the focus on certain new products and technologies, which are then sourced or produced in particular countries. New products may shift the demand and the production quickly.
- Supply-chains are now very sensitive and represent a high risk when looking a potential security risks or strikes. Travel restrictions with related transport limitations pose a danger to the optimized supply chain.
- Production moves (salaries, conditions) due to the increase in salaries and wages, supply chain problems might emerge, or base material availability becomes a problem. As this is the decision with the most cost influence much more factors have to be included when performing due diligence for production site developments. Moving products with production from one site to another relies on the thorough life-cycle management of the product. The basic functionality but also the add-ons to the product features have to be equal, regardless of the production origin. Moreover, this process is dynamic, product and product related production changes must be reflected within the whole production universe in order to keep the technical product design consistent. For the transparent availability of basic parts (e.g. screws and nuts) norms and standards are defined and help. However, the availability of basic products (e.g. steel sheets, cloths) is essential.

Many of these potential risks are more or less obvious and thus can be planned or provided for. This is undeniably one of the primary tasks and responsibilities of the management functions of any organisation. In particular business development, business strategy and supply chain strategy need to be looked at. Environmental and risk analysis provide tools to deal with this kind of problems. However, as usual it is a matter of possible incidents weighted with the probability of occurrence and therefore remotely likely events might not be taken into the calculation as much as more probable events.

4.3 COVID-19 risks

Let us now recall the main effects of the pandemic as we are experiencing in the part months (see General consequences of COVID-19). Any kind of pandemic has three main effects we are experiencing right now. This work now focuses on the COVID-19 specifics, in particular these points then represent the angel points for the management considerations. The risks related to people are presented, the facilities and sites as well as between sites, respectively.

4.3.1 Health management, medical (people)

The danger to world population and world economy is real and the current development shows that the solution thereof must be one of the primary tasks of the management. Companies, with all their organisations and suborganisations from headquarter to manufacturing site have to be protected in order to contain the virus. This includes all possible health measures that have to be taken as suggested by most of the relevant health authorities. Social or physical distancing (1-2 meters distance, avoiding crowds), wearing face masks when in public (or at the workplace), increase hygienic measures such as handwashing and other disinfection measures. The focus in this risk group is clearly on the people's well-being and their health protection.

4.3.2 Isolation management, physical (site)

Part of the physical distancing measures mean that persons or groups of persons have to be isolated in order to minimize infections. This is done with the measured described above. A consequence is that management has to deal with these issues be introducing new (extended) shift models, the establishment of cohorts (group of employees that physically do not meet each other anymore. Home office for administration staff has been introduced earlier as an incentive for the workforce.

However, the recent developments make it necessary, and management has to deal with this by introducing the administrative but also the technical prerequisite to implement these options. Employment contracts might need to be adapted, IT-equipment has to be available, software access and data lines must be available.

This risk category focuses on the consequences of the local (manufacturing) site and the issues that have to be resolved locally.

4.3.3 Lockdown restrictions (global)

Above we focussed on the people and health perspective as well on the local site perspective. The more global issues that arise from the COVID-19 risks are now presented. This is mainly concerning restrictions or actions that are coming from the lockdown restrictions that have been imposed in several qualities. The lockdown has been a measure to implement the isolation requirements mentioned above. This can be done on various levels of implementation and mostly on a regional (country) basis. Mostly, the regulations have been introduced covering the following measures:

- Closing non-essential businesses (restaurants, flower shops etc.), this comes in may flavours but the basic idea is to reduce contacts in public.
- Restriction to businesses only in the essential businesses to keep up basic needs and the infrastructure such as food, pharmacies, phone providers
- Curfew measures to limit the number of people to their home locations. People are only allowed to leave their homes for work related or health matters.[4]

The handling of the counter measures heavily depends on the political systems as well. Requirements such as full contact tracing with mandatory phone apps installation make sense from the epidemiological standpoint, however the implementation of such action in liberal democracies is more difficult than in more authoritarian regimes.

Details to these measures and their implementation vary from case to case. In most countries these measures have been implemented similarly. it all

[4] It has to be mentioned that this is a measure that requires a hight level of commitment in the population, clearly one has to be prepared that some parts of the population will actively work against such a measure, undoubtedly in western liberal populations.

comes down to the limitation of movements of persons (i.e. isolation) in order to prevent the virus to spread among the population.

This is certainly the main consequence that business face around the world when dealing with this pandemic. The limitation in movements of people is primarily influencing the employees, client contact, as well as the supply chain.

The workforce is limited by coming and going to work. For administrative staff this effect can be mitigated by the introduction of the home-office as a work mode. Emailing, social media, and video conferencing are established means to face these challenges. Most countries provide the infrastructure to do so. Even though some might face problems with home space or the availability of childcare in these circumstances. Travel restrictions can be overcome with similar technological and organisational arrangements. This has been anyhow implemented in recent years in most international companies.

However, manufacturing sites and organisations obviously need the physical presence of the workforce, this is more difficult to manage. Epidemiology suggests the process of cohorting to overcome this problem. Basically, workers (people) are grouped in order to isolate them from other groups. The groups are formed to cover all the functions needed to independently function on its own, this is key issue. The groups physically do not meet each other. This approach can be iterated on various levels. It creates a redundancy that allows organisations to function even if infections occur or even if parts of the cohort need to go into quarantine. For factories a similar approach is available. The extension and adaption of shift models applied additional isolation measures is a probate means in order to solve this problem, more elaborate methods for partitioning have been the subject of recent studies [42].

The dependence on the physical presence of the workforce and the need for managing this with extensive care and cost will certainly have an effect on the introduction of Industry 4.0 projects. The investment in automation and robotics technology is substantial, however the increased cost for handling the pandemic cost related to the workforce will have an effect on the feasibility of new automation projects. This will rather apply to high end manufacturing than on low skilled workforce. A transition from low labour cost from the developing world to advanced economies might become more feasible [43].

International client visits represent a further challenge. Travel limitations restrict people in general in their movements, this also applies to customer

visits, from both sides. Client presentations or visits on sites are no more possible. This can partly be overcome by video-assisted presentations. However, the tactile and personal experience is missing and has to be compensated with personal attentiveness towards the clients. Top management and sales contacts can deal with this issue, even though difficult. A more challenging task is contact required when physical work needs to be done on site. As an example, consider a manufacturer of made to order assemblies that need inspection and approval in order to ship products or components. This is usually a process that requires persons involved. Either for measurements that are taken and approved or for function tests on site. As in the case of general client contacts the possible solutions are the involvement of video conferencing as well. In addition, the local support during the inspections can be helpful. The process would then involve remote instructions for testing and taking over the equipment. The local contact would then execute the test procedures and feedback with the necessary documentation. Needless to say, that a necessary level of trust is required in order to smoothly go through the procedure.

It has been pointed out above that in case of isolation measures the lack of physical contact can be mitigated, even in the case of the client contacts. Given the restrictions to move a further challenge has to be managed. It is not only people that move, but also equipment and goods. In general, the logistics chain includes not only the movement of goods but also the people who move the goods with them. Consider deliveries that have to cross borders. Lockdown measures between regions with different pandemic statuses that require isolation cannot be entered or passed. A problem, that can only be mitigated on the intergovernmental level or at least neighbouring countries. The European Union has up until now not faced this type of problems, the standard freedom of goods regulations is still in place. However, this could change further down the road and face severe problems in the interchange of goods.

4.3.4 Implementation efforts, disturbance

The various risks discussed above are shown in the following table. The various risks are then grouped into topics. A measure of implementation efforts has been added. This indicator specifies how demanding the related consequences are. It indicates a *category of disturbance*:

- Low or short-term disturbance (L) can be mitigated rather quickly with relatively and reasonably low cost involved.
- Medium disturbance (M) requires a longer transition time of 3-6 months and comes with a higher than usual cost tag. Given the potential duration of the disturbances, these costs can mount up considerably.

- High disturbances (H) are caused by risks that need considerable efforts for change. In the latter case we look at long-term projects (> 12 months) that will usually require extraordinary budgetary requests which would then consequentially need board involvement.

The classification in the table below groups the risks into three main categories. It then relates to the typical action that is required. Requirements can vary along the line of industries, countries/regions and infrastructure.

Risks	Implementation efforts
Health Risks (people)	- health checks, regular examinations (L) - virus testing (L) - anti-viral hygienics (L) - temporary replacement of personnel (L) - long-term replacement (M)
Isolation Risks (site)	- personnel measures (L) - personnel cohorting (L) - increase in staffing (L M) - changes to personal flow (M) - changes to material flow (M)
Lockdown Risks (global)	- internal travel restrictions (M) - client travel restrictions (M) - supply chain, material/products (M) - quality checks at suppliers (M) - site related changes (M H) - supplier management, new suppliers, localization (H) - product related, adaption for local or alternative production (H)

Table 1, Risk categories with severity and disturbance measures

Health risks are related to direct threads to the health of the workforce and the related persons involved. Isolation risks are risk that are coming from the isolation efforts required to curb the disease. Focus is hereby on actions on site at the factory location. Lockdown risks cover all the risks that are related to the actions coming from the lockdown, between sites. Essentially, they are affected by the limits in the movement (of goods and persons), focus is hereby all external action.

It is needless to say that all these risks with the respective implementation actions come with sometimes considerable cost attached. The cost is caused by various aspects and can range from simple action with relatively low budgets involved to very high cost and long implementation periods.

The changes require the purchase of tools and health items for the health risks. The cost for reorganizing workgroups, introducing cohorting and other mitigation elements such as the introduction of redundant workforce can be significant. In addition, the time required for implementation must not be underestimated.

The highest cost involved are the actions that are coming from lockdown risks; especially medium and long-term risks that involve changes in the technical product design to accommodate further suppliers or the introduction of new routes in the supply chain. The highest cost can be expected when changes to the production setup are required or in the case of the ultimate consequence production sites have to be moved or even closed in the course of the risk mitigation efforts.

4.4 Corrective and preventive actions, factors of robustness

The risks and responsibilities were detailed above. These are now combined in order to come up with counter measures that can be used to when facing COVID-19 related risks. We see the risk mitigation efforts can be seen as pro-active measures whereas the counter measures are the outcome of immediate reaction to a risk.

In previous decades the reduction of cost or the minimization of throughput times has been set as the priority when looking at technical product designs and factory design. Nowadays, with the restrictions in place that were mentioned above the focus shifts to redesign processes and organisations pro-actively. This redesign is targeting the following factors of robustness:

- resilience,
- redundancy, and
- flexibility.

Organisations and their processes have to become more resilient. Resilience describes the ability of a company to fulfil its tasks and responsibilities even if some of the infrastructural or environmental condition fail or are deeply disturbed. The main concern is the robustness of the processes when disturbed. The organisation must be able to recover from failures, catastrophes or abrupt changes in the environment One of the infrastructural conditions is the freedom of movements for goods and personal. COVID-19 is certainly affecting this. Making processes and organisations more robust is challenging and sometimes conflicting other tasks and targets. Consider the production with base material that can be sourced from different parts in the world, or even locally. Clearly having

locally sourced material is more resilient than having to rely on products that have to be transported under difficult conditions.

Redundancy represents a similar measure. It is a concept that opens viable alternatives in case primary solution patterns fail. Consider the availability of a stable data line in order to connect to other locations or the world in general. Reliance can be achieved with installing a performant backup line that can be of service in case the primary fails. Moreover, the technology has to be different in order to prevent the backup solution relying on the same technology as the primary solution. However, this solution is mostly conflicting with the cost targets that have to be considered. Having backup solutions in place usually increases the cost.

A careful analysis has to be the source of the backup scenarios in order to provide for both targets. It has to be pointed out that the reduction of redundancy has been the primary target of reengineering and optimization efforts up to now. For current considerations it can become an asset though. Reducing redundancy and increasing resilience can be conflicting tasks and management has to set the priorities in this case.

Flexibility is a further available measure. When dealing with the disruptions we are currently facing, we are required to assert much more flexibly that in the usual standard situation. In general, non-pandemic, situation we focussed on streamlining processes and businesses. Processes were optimized in reengineering projects and focused on the optimization of the tasks. To a considerable extent the reduction focussed on reducing material or reducing (unused) time. The reduction of idle times in quality management lead to a lean process and established a whole new view on how production is done. The optimization of the material usage and availability lead to the reduction of (internal) stock and introduced optimized supply chain organisations that synchronized material availability along production lines.

Businesses facing the disruptions caused by the pandemic have to rethink all these paradigms. The current difficulties of getting goods, services and people at the right time to the right place will inevitably stretch the 'optimized' time schedules that were assumed in earlier process schedules. Having (emergency) stock in place or switching to locally available purchasing will help to regain resilience.

But these initiatives come with a price attached. The process optimizations earlier were partly driven by cost reduction programs. Reintroducing slack and stock are flexible measures in order to regain resilience. These counter

measures certainly have consequences and will have a considerable influence on the production cost.

Again, the efforts that have been taken in optimizing the supply and the production chains were based on the optimization paradigm of streamlining the processes and reducing waste of any kind, thus resulting in reduced cost. In case of reversing this via risk mitigation, the cost will increase for most of the corrective and preventive actions taken. This is one of the most important topics that have to be included in the decision processes.

4.5 Risk mitigation

This section introduces the measures that can be applied to increase resilience, redundancy, and flexibility in the field of distributed manufacturing. For the further analysis and a clearer view we introduce the company size and the depth of the measures.

As a further dimension the depth and timeliness and the effort required to implement the corrective actions is introduced. With shallow measures immediate action with an implementation time of 3-6 months is assumed. Short- or medium-term action are for example changes in internal regulations (travel), cohorting of workforce, or partial renegotiation of purchasing contracts. Deep activities and preventive actions on the contrary represent action that is considered rather long-term. In addition it considers projects that require a more profound analysis and elaborate action plans. Certainly some of these projects would also require additional capital investment (such as moving production sites), or reengineering projects resulting in automation or the shift to Industry 4.0.

Deep and shallow measures relate to the time and ease of implementation but also to the related cost that are involved. Especially the medium (M) and high (H) risks lead to a substantial increase of operating cost and if required a considerable capital expenditure.

In the following this thesis describes how to extend the general tasks described earlier with the special tasks that can be performed in order to face the pandemic. Actions for the risk mitigation are proposed.

The table is made up as follows. The columns cover the risk factors that may occur in the before mentioned categories; health, isolation, lockdown (see COVID-19 risk). The rows contain the various production and management factors that were proposed above (workforce, products, supply chain and materials, equipment, IT, quality management and partners.

Factors	Health (people)	Isolation (site)	Lockdown (global)
People	COVID-19 testing (L) hygienics (L) social distancing (L)	Cohorting (L) Video conferencing (L) Home office (L) Temporary replacement of personnel (S M)	Build up redundancies, multi-site (M) Short-term and long-term replacements (M L) Staff increases (M L)
Products and process management	COVID-19 testing (L) hygienics (L) social distancing (L)	Localization of production and sourcing requires local adaptation of PLM (M L)	Prep for rerouting of production to group members (M L), increase localization (M L H) Keep PLM systems updated and coherent in case of changes (M H)
Supply Chain, Material	COVID-19 testing (L) hygienics (L) social distancing (L)	Build-up stock for basic material (S M) Pre-order half-finished goods, stock up (S M)	Pre-ship finished goods to internal and external clients Get new local suppliers (M H) Prep for client requirements on their stock increases (M)
Equipment, production concepts	COVID-19 testing (L) hygienics (L) social distancing (L) Cohort operating and maintenance teams (L)	Schedule pre-emptive maintenance (S M) Local machinery redundancies (M L)	Group redundancies in machinery and equipment suitable for rerouting (M H) Reengineer for Industry 4.0 (H)
Information Technology (IT)	Cohort maintenance teams (L) remote administration (S M) Introduce videoconferencing tools (L)	Remote administration (L) LAN speedup (L)	WAN speedup (L) WAN, alternate routing options (M) Insourcing of critical cloud services (M)
Quality Management	COVID-19 testing (L) hygienics (L)	QM personnel cohorting (S M)	Redesign take-over procedures for remote quality checks (M H)
Partners, Communication	Keep up information flow for potential visitors about rules and regulations (L)	Introduce videoconferencing for externals (L)	Engage in local governmental task groups in order to facilitate govt action (M H) Long term factory planning (RCEP, TTP) (H)

Table 2, Corrective actions, resilience in distributed manufacturing

The cross-sections in the scenarios will address the corrective actions and will differentiate along the company size (SME) and the type of countermeasures wherever applicable. Then, specific examples and elaborate more in detail for selected mitigation action will be presented.

For the company size we differentiate between on small and medium enterprises (SME) and large enterprises or production units. For definition purpose we refer to SME enterprises according to the European Union definition[5].

4.5.1 Scenario analysis

In the following some of the aspects depicted above describe will be described in more detail. Consider the simplified scenario and setup of the producer of widget A. The company has several distributed manufacturing sites and products. The production of widget B and C is completed in P2 and P3, respectively.

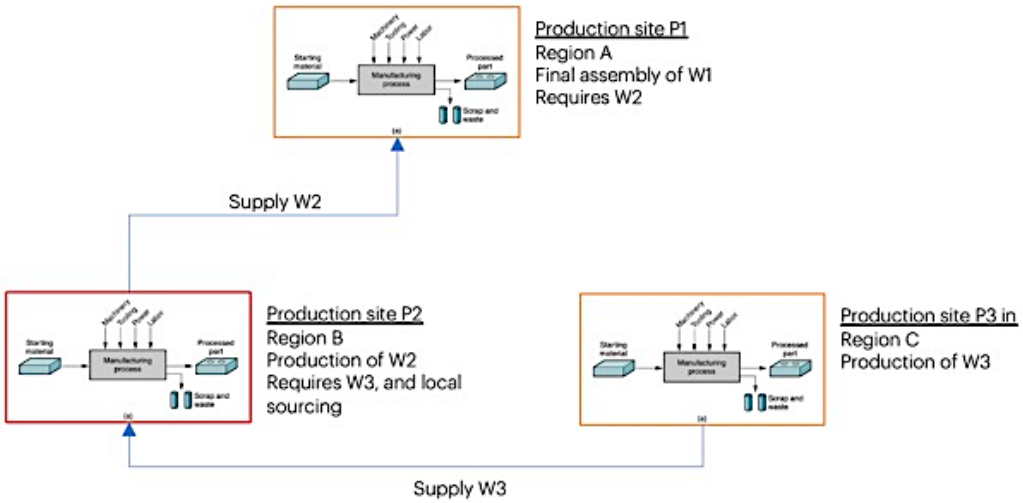

Figure 15, Scenario, basic setup

For the sake of simplicity, we assume that the production is distributed in two supply productions P2 (in region B) and P3 (in region C), the final assembly is done in production P1 which is located in region A. The final assembly of the end product widget A requires widget B and C at site P1 in region A. P2 sources locally and in region B, P3 sources locally and in P2. The clients are

[5] 'The category of micro, small and medium-sized enterprises (SMEs) relate to enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million' [48].

located near P1 in region A. Given as well is the COVID-19 outbreak in the regions A, B and C. Region B (including P2) has very high COVID-19 incident rate and therefore the authorities imposed a complete (region-wide) lockdown[6], whereas region A and C (including P1 and P3) have a partial lockdown[7]. The latter makes it easier to move product and people, but restrictions are resulting in considerable supply and transport issues.

4.5.2 Scenario 'Supply Chain' (rerouting, move production line)

Let us now consider the available options for the supply chain. We try to put special focus on the feasibility of the action. This is particularly of importance when looking at the size of the company and the shallow or deep implementation options. Keep in mind that any action taken has the potential to turn into increases of operations cost.

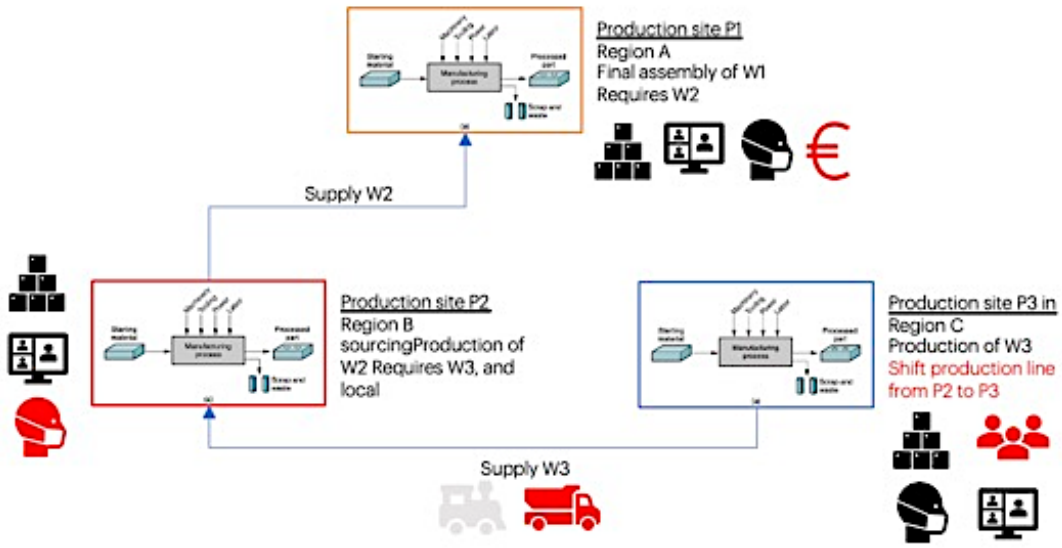

Figure 16, Scenario 'Supply Chain'

For substantial projects such as the move of machinery or production facilities this requires most likely considerable mid- or long-term investment cost.

[6] Complete lockdown: schools, shops and restaurants are closed, public transport limited, factories and suppliers operate, but under hard and difficult conditions, delays are frequent.

[7] Partial lockdown: schools, shops are partially open, restaurants closed, public transport limited, factories open, delays are possible but manageable.

- P3 is a site producing widgets 3, a shift to P2 is considered feasible
- P2 needs either to develop a new supplier for widget C or a move the production
- Base materials and semi-assemblies are stocked up at any site
- Transport options from P3 to P2 are considered
- P3 has to prepare for a hard lockdown and needs to ensure production by taking in temporary personnel, administration and HR tasks are to be streamlined for this, training programs must be invoked.
- Home office and video conferencing has to be set up at all sites
- Health related tasks such as regular testing, health procedures have to be put in place

The following action will be taken. We have included the presumable effort that is required to implement the actions that are taken.

Supply Chain	People	Site	Global
P2	-Impose health related measures such as COVID-19 testing and hygienic measures (L) -move personnel from P1 into P2 is necessary (M)	-Increase the stock levels of base materials (L) -sourcing or producing widgets C locally in region B (M) -introduce production line for widgets C (H)	-Stock up widgets C from P3 (L) -Establish individual transport from P3 to P2 in order to get widget C in time (L)
P3	-Introduce Home office for admin staff (L) and video conferencing (L)	-Increase stock of base material (L) -Establish individual transport from P2 to P3 (M)	-Prepare for hard lockdown in region C by establishing alternate transport routes to A (M) and preparing temporary personnel intake (M)
P1 (with headquarter)	-Introduce Home office for admin staff (L) and video conferencing (L) -Increase support staffing for P2 and P3 (M)	-Consider alternative transport from P2 to P1, train instead ship (H)	-Shift production from P2 into P3 or into P1 (H) -Make sure product features and standards meet requirements from region B and C, to make it interchangeable) (H) -Stock up banking lines within the group for higher material sourcing requirements

Table 3, Supply chain, corrective actions

Because of the hard lockdown in region B, P2 finds it very hard to get the supplies locally and the import of widgets from P3. Workers find it more and more difficult to find their way into P2. Suppliers face the same problem; imports are becoming more and more difficult. The mobility of workers is limited. First, Establish the health-related action plans for all regions, regardless of the lockdown levels. However, adjust it to local and legal requirements in regions A, B, and C.

Then the stock levels of the base materials are increased. Management decided to look into the local sourcing of widget C in the region. Given the limited availability it is planned to establish a local production of widget C in P2. This requires also a redesign of some of the production features of widget C in order to maintain the technical and design functionality of the product. In any case the stock levels of widget C in P2 have to be increased, considerably. Given the transport problems between the two sites it was decided to shift from train to cargo trucks.

The cost involved are considerable and include health cost for the local production, cost of capital for the increase of stock levels for both base material and widgets C, and increased cost for truck transports. The biggest increase in cost is related to the establishment of an additional production line of widgets C. Ensuring production quality and consistency with the technical production design of widget C when produced in a new site is heavily relating also to P1 where the final assembly will take place. The closing of P3 will be an option if and when the local production (or local sourcing) of widget C in P2 is completed.

It has to be pointed out that some of the action possible for action heavily depend on the market position between the supplier and the buyer's organisation. In particular, when it comes to supply chain issues it is usually the supplier who has the task of intermediary stock management. As a rule of thumb, small and medium enterprises have to mitigate risk for the benefit of the larger organisations.

4.5.3 Scenario 'Industry 4.0' (site closing, advanced manufacturing)

In the following, concept will be extended by introducing the model of Industry 4.0. It has been pointed out earlier that the risk mitigation may bring opportunities for the introduction of Industry 4.0 concepts.

For our example scenario some of defining restrictions will be introduced. Initially, P2 was established because of low wages in region B, meanwhile the salary difference between P1 and P2 has narrowed, but still being smaller. In addition, recent political and economic events lead to a more isolationist

policymaking, which in turn led to the establishment of a regional trade and tariffs union. As it evolved, the goods transport from P3 to P2 and from P2 to P1 has become more and more difficult due to the establishment of tariffs and import/export restrictions.

Furthermore, the main **market** in region A begins to **shift** from mass product demand towards individualized production of small lots, clients are more and more demanding 'smart' widgets. Smart in this respect means that the products need to be programmable with 'internet of things' logic, a development that thus requires a follow-up of the technical product design.

After product and market research a **new technical product design** is introduced. Apart from market and customer considerations, manufacturing concepts are also required to adapt. Therefore, management decides to set the focus on flexible and local manufacturing in small series. Therefore, the feasibility of a reengineering program with the introduction of Industry 4.0 concepts has become feasible and necessary.

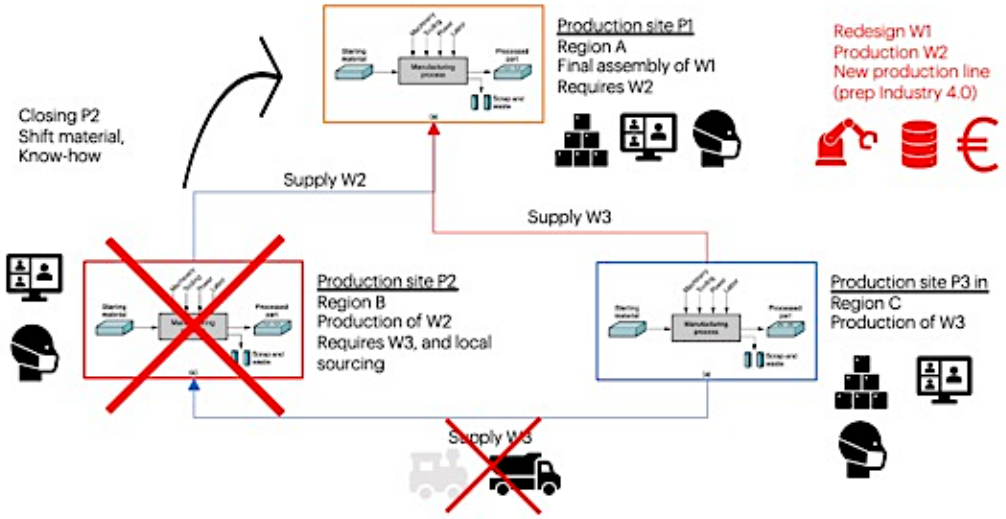

Figure 17, Scenario 'Internet 4.0' (re-engineering)

However, it would completely change the setup of the whole manufacturing within the group. The targeted setup can be described as follows:

- Technical product design evolves to 'smart widgets', design team are facing a most demanding task
- Small series production in region A puts the products more into the reach of the clients, requires new automation concepts leaning towards 'Industry 4.0'

- Close the factory site P2 and move parts of the production to manufacturing site P3 (partially due to raising trade barriers due to a new regional trade union)
- Redesign the widgets A in order to include programmable memories (towards IoT functionality)
- Changing the product design of widget A will have also consequences for widgets B and C.
- Home office and video conferencing has to be set up at all sites (advisable in any scenario)
- Health related tasks such as regular testing, health procedures have to be put in place (advisable in any scenario)

Industry 4.0	People	Site	Global
P2 (closing)	-Impose health related measures such as COVID-19 testing and hygienic measures -Keep ppl on board for product transfer (M)	-Prepare phasing out of production site (L) -Initiate site salvation program (M)	-Establish a (global) knowledge transfer team for migration from P2 to P1 (H)
P3 (extending)	-Impose health related measures such as COVID-19 testing and hygienic measures -Training P3 (M)	-Make sure that open topics can be taken over from P2 (M)	-Transfer all (product, material, production) databases to P1 (M H)
P1 (incl. head quarter)	-Impose health related measures such as COVID-19 testing and hygienic measures (L) -Install a reengineering project group (L)	-Reengineer Widgets A, B, C so they can be produced locally in P1 (H) -Product development program for 'smart widget A', programmable, add product functionally (H)	-Prepare base material for widget B is available in P1 at same qualities and quantities (H) -Prep the market introduction (M H)

Table 4, Reengineering, Industry 4.0, corrective actions

It has to be taken into account that the targeted changes are a non-trivial at all. It is a tremendous change for any organisation and will certainly not only take years for implementation, but also require a substantial capital investment in time and funds. Usually, small and medium company are less apt to undergo such a transformation, given the often very limited financial capabilities. SMEs could also consider this transformation as a chance rather than a threat.

The view presented in the scenarios can only represent a guideline and a general direction, rather than a fully planned and elaborated scheme of works that need to be done. Both examples, supply chain and the introduction of product redesign and advanced manufacturing technology require a lot of preparatory word and also considerable amounts of funds in terms of capital investment. Reacting to risks thus cannot only be seen as a passive moment when dealing with threats but also a more proactive undertaking in order to create opportunities.

A further momentum is created by the size of the company, action denoted as 'S' and 'M' are usually within the possibilities of any size of the company. Most small and medium companies cannot dispose of some of the 'H' denoted mitigation action. This is due to the timeframe and the capital requirements. Furthermore, some action, such as stocking up will certainly be mandated upon from the larger/stronger to the smaller/weaker units. Risk and cost of the increase of stock will usually be at the burden of the weaker part.

5. Opportunities and prospects

This thesis has until now focussed on the risks, threats and corrective actions that come with the COVID-19 pandemic. This is an expected approach when mitigating a crisis. Certainly, the action taken makes sense when facing the immediate threats. The analysis and the immediate action taken is hence very valuable for the reduction of the arising risks. The effects are decreased or in some cases even eliminated. In any case, awareness is shaped, and the overall business process continues and is less disturbed.

We have introduced increased resilience, redundancy and flexibility as means to mitigate against these risks. Special focus on these issues from the perspective of proactive management are now presented in the following section.

Though, threat mitigation represents only the first step when dealing with any crisis. The measures taken are as described: increasing reliance, redundancy, and flexibility of the businesses and organisations. It is certainly a necessity for economic survival to take action and get along with the pandemic risks. But the steps are taken after the crisis hits the organization. In some cases the disruptive event is so rare that there is no other way. In this case of the COVID-19 crisis we should consider it as a proactive way to look at all business-related matters. Nonetheless, the action taken, are strengthening the organisation and leading to a more resilient business setup. It will strengthen the business and at the end it will lead to a benefit.

The competitive advantage that is resulting from managing the crisis is at hand is obvious. Particularly the following issues can be considered rather an option in the crisis than an overall negative development:

Adding more robustness, resilience, and flexibility in supply chains and processes represents a fundamental mitigation task. Companies that do not tackle this task will find themselves in a position where their clients might move on to other suppliers. They must react and take the changes into effect; any other action makes them difficult to compete in the markets. In addition, the next crisis or pandemic might just be around the corner. Predictions as to when this will happen are difficult to establish by nature but tackling the problems at hand will certainly prepare for the next crisis.

Having procedures and emergency plans in place that help to face and mitigate risks will benefit in any case. Looking at these action plans without actually facing a direct threat will bring valuable insight into the options available for better future business processes that deal with uncertainties.

The preparation of the corrective actions and the emergency plans to invoke them are providing valuable data for shaping the organisations to increase efficiency. Elaborate scenario analysis is a tool to achieve this. The resulting pre-emptive risk analysis outcome creates insights into the vulnerabilities or processes or organisations and is of tremendous value. Other disciplines such as military command have established this already earlier.

The competitive advantage resulting from the risk mitigation is not only restricted to companies and organizations. Governments, local or regional, are as well in competition. In the course of the pandemic we see some countries that take a rather neglectful approach when implementing actions against the pandemic. Others are using the momentum for policy changes, reorganisations and streamlining of government processes.

As a result some companies and countries and their economies will come out of the crisis not only faster but also more robust than others. The first developments are already confirming this. At the end this will be an economical advantage that will consequently result in a more competitive industrial and economic base than before. It is part of the infrastructure and the stability of the economic environment represents a major factor for growth and development.

6. Summary, conclusion & outlook

Globalization conditions thrived over the past decades. With it emerged the distributed manufacturing operations that covered almost all of the industries, regions, and countries. The international network of manufacturers, sub-manufacturers, and integrated logistics companies organized the industrial throughput to an almost perfect system. The routes of the products between material and product suppliers and the clients or end customers have been optimized. Moreover, the manufacturing throughput times and the speed to market reflect this development. This speed up allowed for new product(ion) models at a large scale and had tremendous consequences. The production cost of almost any product was considerably reduced. Dropping consumer prices reflect this development as well. In addition, the company profits went up. The contribution to the GDP-growth for any involved country in this supply chain is undisputed.

However, the disruptive event of the COVID-19 pandemic appearing in 2020 changes the rules of the game. The pandemic was called in early 2020 and unfortunately took most of the countries and organisation by surprise. Even though similar viral disease and pandemics appeared in earlier centuries, everyone was caught by surprise and corrective actions had to be developed on the fly. At the end, it was science (epidemiology, virology) that recommended he appropriate and effective countermeasures such as health related measures (e.g. disinfection, facemasks, social distancing), lockdown and isolation measures (home officing, video conferencing, cohorting, reduction of contacts in general) for immediate action. The vaccine development started immediately with the emergence of the new virus, first results are visible and some of the vaccine developments are already on the market. More than 70% vaccination coverage has to be achieved in order to get to the desired and safe herd immunity levels. However, the large-scale availability in OECD countries cannot be counted on before the 3rd quarter of 2021. Bulk availability on a world-wide scale will have to wait until 2022 earliest. As a consequence, disease will be with us for some time.

This thesis covers an analysis of these issues and proposes suggestions for the mitigation of these risks. The introduction describes the development of trade and distributed manufacturing over the centuries until the elaborate distributed manufacturing models we know of now in the 2020s. The thesis then explains the development of pandemics in general, and the imminent disease known as COVID-19. The general consequences of any particular pandemic are analysed. The characteristics of the COVID-19 condition are presented. The risks and the mitigation action from the pandemic are then

set into relation with the tasks and responsibility of general management decisions, in particular related to modern distributed manufacturing.

The outcome and the lessons learnt from this ongoing pandemic are manifold. Related to manufacturing they are rather simple and straightforward. In the recent years, companies have optimized systems, processes and organisations to a great and necessary extent. The engineering and reengineering profession as well as quality management eliminated slack (lead times, buffers, excess stock levels or alike), waste (material optimization, processes), and excess of time out of the processes and procedures (product and process engineering). Supply chain optimization added to the success by reducing the intermediary time between (distributed) processing even more. The benefits were clear and obvious. Processes became faster, cheaper, and optimized to a great extent. However, as a consequence, the resilience, robustness, and flexibility decreased. The supply chains became more vulnerable and more inclined to interruptions and delays, with disruptive consequences as we painfully experience throughout this pandemic.

These problems and disadvantages have to be overcome with a clear mind and with thoughtful action. The processes and supply chains have to be re-engineered (sometimes back). Systems and processes must become again more robust and resilient in order to show the flexibility that is needed to face such disruptive influences. Redundancy has to be re-introduced wherever necessary and affordable. It has to be kept in mind that in the previous optimization and reengineering steps the reduction of redundancy was a key element in process reengineering. The success of the reengineering tasks was measured in the reduction of slack and the decrease of throughput time. As an advantage, optimized manufacturing and supply chain processes were developed, with reduced cost, respectively. However, the existing processes were now lacking resilience and robustness. This thesis suggests increasing redundancy, robustness and flexibility. More stress must be put on crisis-resilient processes in order to overcome the problems we are facing now. Examples and suggestions are given, based on a simplified scenario of a distributed widget producer. A set of actions is proposed and categorized into **health** risks, local site related **isolation** risks, and global actions (as **lockdown** risks) were presented. The mitigation actions described were grouped **low**, **medium**, and **high** - from easy to achieve (in time and cost) to long-term targets that require considerable efforts.

This thesis introduces mitigation action (corrective and preventive) along several dimensions. Firstly, the factors needed in a production environment are analysed:

- Production factors
  people, products and process management, supply chain, equipment (production concepts), information technology, quality management, and partners.

As a further dimension to the problem, the risk groups that needed to be considered are included in the analysis. It basically consists of grouping the targets of the action into the categories people, sites, and networks.

- Risks (health, isolation, lockdown)
  health considerations for the people involved, isolation action that is required within the site or the organisational unit, and lockdown risks that refer to the action that is required to mitigate the risks between units when dealing within a network.

These influencing factors are then combined into actions in order to increase the robustness factors described below.

- Factors of robustness
  Resilience, redundancy and flexibility.

The analysis shows that some of the actions are short-term with a speedier time frame and presumably lower cost factor, while others are rather long-term with higher cost attached. A further differentiation comes along the dimension of company size. Some companies are limited in scale and thus have less financial leeway for such large-scale change. However, this disadvantage can also turn into an advantage given the resistance of change sometimes inherent to large organisations.

An example setup of a widget company and developed two example scenarios: 'Supply Chain' and 'Industry 4.0' are given to exemplify approach. In the first example, the disruption of a two-factory setup must be overcome. The proposed solution focusses on changing the supply chain strategy as well as the stock levels for certain materials and (sub-) assemblies. In addition, alternative transport routing is proposed. The suggested solution of the latter example is more complex. In addition to the supply chain and stock level related action, it is proposed to reengineer the widgets. This would result in the closing of a production site and the newly setup of a production site near the client market, thus becoming more resilient to stock and transport risks. The product reengineering part suggests a change in the product design to allow for production in smaller lots with a higher variability based on customer requirements. In addition, the widgets are added 'intelligent' functions by using smart components. Health related measures are obviously suggested for all of the scenarios. It must be emphasized, that any of such projects are lengthy and sometimes with high implementation risk.

In any case they are requiring considerable funds that must meet the requirements of business plans and budgeting restrictions.

In a nutshell, the risk mitigating actions to cover disruptive events such as the COVID-19 crises can be summarized as follows. Bear in mind that these actions are not only a remedy for when dealing with a threat such as the crisis we are facing momentarily. It also serves as a blueprint for pre-emptive action that can be taken to strengthen the businesses and processes before such crisis will happen:

- Increase resilience and robustness by adding viable alternatives to supply countries, transportation routes, material availability. Material requirements are therefore not limited by anymore, the determining factors for material purchasing and material logistics are extended by resilience increasing factors such as the topics mentioned above.
- Stock levels are a common and reliable means to gain flexibility when dealing with supply chain problems. As helpful as it is in the short and medium term it has to be pointed out that we are looking at considerable cost increases when increasing stock levels, both profitability and liquidity of financial assets are concerned.
- Strengthen the material base by adding more qualified suppliers (from different regions), reengineer your products in order to allow for more material varieties.
- Product redesign as in one of the examples above is the option with the most thorough consequences, it has the potential to change the setup of the whole business. Therefore it is also the change proposes that requires meticulous care when implemented.
- Production setups must be kept as flexible as possible in order to be able to deal with a variety of materials and sub-assemblies. In addition, rearrangement and even moving production must be kept in mind when planning and implementing production sites.
- Protect workforces by adding redundant setups in the locations. Also the deployment options of the workforce must be more flexible, training and qualification programs can help to get this done. In addition, the increase of health-related measures such as hygienic concepts are viable.
- Cost considerations must be kept in mind when dealing with changes of a certain scope. In particular, building up stock to get more resilient process supply chains can be tricky and result in a considerable increase of operating cost. Similarly, the move of production sites or the redesign of products usually requires heavy investments and thus higher production cost.

All the suggested corrective actions are posterior measures to the event of a crisis. However, it can be used in further scenarios as preventive measures. Firstly, when industrializing new products and setting up new industrial sites, the analysis delivers as very useful and will provide insight in the way to come up with more resilient and flexible business setups. Secondly, even without an actual imminent threat the analysis can be deploy an analysis of weakening points of any organisation, either for the preparation of the next pandemic or any other threat of disruption. The thesis takes up this idea and closes with an outlook of positive consequences the corrective and preventive actions will have for future business opportunities. It must be pointed out once more that any analysis along the introduced factors can be used in any threating situation, not only the current pandemic. Therefore, it helps to strengthen the organisation in general and against a great variety of risk classes.

The robustness and resilience of the business processes will not only help to stay in the market but also represents a competitive advantage.

A final quote from A. Einstein that is more than a mere catchphrase and it undeniably comforts on the way forward

'in the midst of every crisis, lies a great opportunity'.

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