EXPLORING IDEAS TO FOSTER THE METAVERSE

April – June 2023, by Roberto Saracco

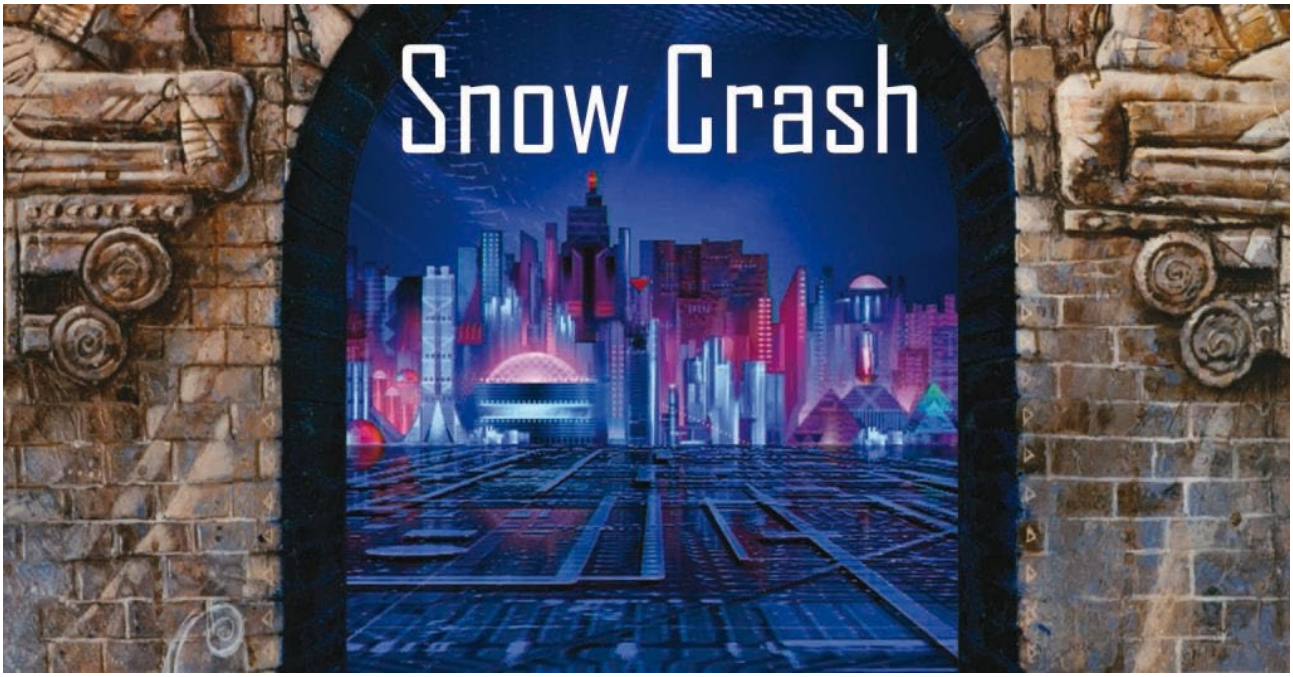
This eBook is based on a series of posts published in April-June 2023 on the IEEE Future Directions Committee website (cmte.ieee.org/futuredirections) by Roberto Saracco. There are other posts on this topic and more will come as the IEEE Metaverse Initiative progresses.

Make sure to check the blog for latest thoughts and to share your ideas on the topic.

For general questions about the IEEE Metaverse Initiative, please contact metaverse@ieee.org.

Table of Content

Exploring ideas to foster the Metaverse



The word Metaverse first appeared in a 1992 novel, Snow Crash by Stevenson. It indicated a virtual place used by novel characters to escape from an “ugly” reality.

However, looking for the roots of the word is a bit like saying that “robots” are rooted in a Czech word and in the 1921 play of Karel Capek RUR – Rossum’s Universal Robots, to describe forced labor. It makes for a nice anecdotal reference but does not really help in the discussion, and most importantly, in the evolution and implementation of the idea.

The Metaverse has become the talk of the town, particularly after Mark Zuckerberg announce to change the name of Facebook parent company to Meta, highlighting both the vision of a future where the Metaverse would play a significant role and their commitment to pursue its development.

What is the Metaverse? Since it is work in progress it would be better to state what the Metaverse should be, and here lies the problem. Different companies, different people have different ideas on what it should be and even more different opinion on how to get there.

The difficulty is compounded by the emotional aspects of something that is bound to become (one of) the ambient where we are going to live. Besides, we know from experience that as we create new ways of applying technology, those applications will backfire leading to a change of our perception of the world and to our behaviour in the world.

The IEEE Future Direction Committee Initiative on the Metaverse aims at providing both a vision and a path to implement that vision. As it has been stated by many, we are most likely going through a phase where several “metaverse” will be created and used, not necessarily competing with one another, most of the times flanking one another, responding to specific needs and application areas.

The FDC initiative is working on a White Paper where a distinction is made between “industrial” metaverse(s) and experience metaverse(s) the latter being an evolution of the “Second Life” wave and finding application with the general public in entertainment (gaming, exhibitions, tourism, …) and social relations.

In this ebook I am sharing ideas (and facts) mostly on the industrial Metaverse to solicit ideas, thoughts and experiences that can contribute to the work being done.

I have already touched on the topic of the Metaverse in several posts, in this series I plan to provide a more structured discussion that reflects the organisation of the White Paper under development.

Proto-Metaverses

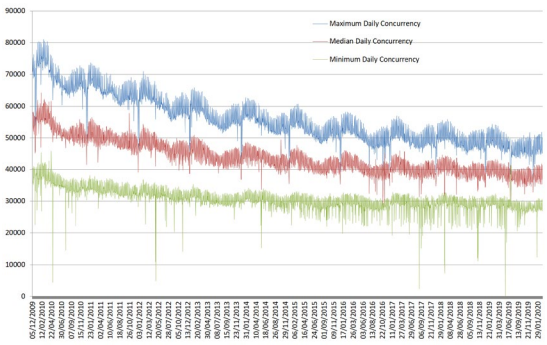
Notwithstanding the fuzziness of the term “metaverse” most people would agree it is a “space” where some sort of life can be lived. Since we are already living a file in the physical space these other “lives” should be flanking the one we are , augmenting it with sensations and capabilities.

Technology has been augmenting our capabilities for eons, and in the past 75 years has opened up the world of bit, a very tiny world to start with that has become an immense space, so large in fact that we cannot explore it without leveraging on tools that can make sense of this vastness, i.e. artificial intelligence.

It is the rise of computation capabilities, artificial intelligence and of devices that can act as gateway from atoms to bits (from our senses to digital representation of bits) that has led to the idea of a “metaverse”. As technology progresses so does the “metaverse” and our perception of what it is and what it could become.

Indeed, in the past two decades we can trace the birth of some sort of proto-metaverse(s) such as:

- Second Life was in a way an example of a metaverse duplicating a (imaginary) physical space in the cyberspace to be used by a variety of constituencies. We are saying “was” because the emotional impact it generated is long gone, but the application is still being used today, and it has evolved quite a bit in the



Graphic showing the actual use of Second life in terms of maximum number of people present at the same time in the virtual world (blue line), the average number (red line) and minimum number (green line) from 2009 to 2020. The decline is clear but there are still users spending time in this proto-metaverse. Image credit: Second Life – Daniel Voyager

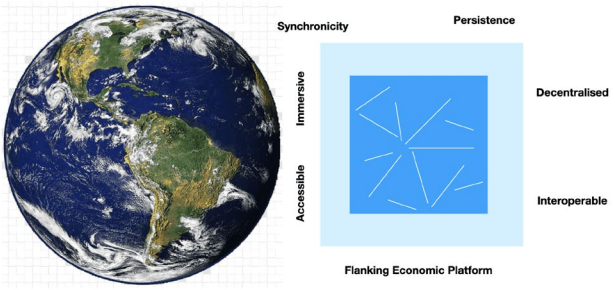
rendering of a digital space. The graphic shows the evolution of this space in terms of users being present, live, in that metaverse at any particular time. The figures are declining but still in the tens of thousands. As of June 2021 there were some 70 million users registered, quite a few indeed, but the number of active users is far less. The number of people "being" in Second Life at any time is around 40,000 Compare these figures with the number of users on Facebook (2.85 billion as of June 2021) and daily users (1.9 billion) and you get the feeling. Besides, Second Life was/is a space fragmented in islands (grid), some 27,000 as of June 2021, so that the roughly 200,000 visitors per day are split over the grid, resulting in a very scarcely populated space. The basic idea in Second Life is to recreate, digitally, the physical space, taking advantage of the increase capabilities offered by a digital space.

- Zoom (and the likes) has become a large success in terms of adoption during the pandemic. More than that, it has created a new culture of meeting in the cyberspace with a growing number of features aimed at providing a better look and feel… In some cases, one can forget of being separated in space and can feel like being present with all the other participants is a "communication space". Features letting people set up their own backdrop (a nice beach on a secluded island, a busy office environment, …) can create a sense of being transported in a different space. It is a space where it is possible to have real time transcript of what is being said, even in different languages, something that won't be feasible in the real space. May be calling Zoom a metaverse is stretching a bit the concept but the idea of having a meeting, or a family gathering as we often did during the pandemic, using the cyberspace is a sort of a metaverse.
- Google Maps with its "street view" can provide the feeling of being there, where the "there" is actually a digital representation in the cyberspace of a physical location. Plenty of businesses pay you to be part of the Google Maps and offer e-commerce services at various levels of sophistication. Here too calling the maps a metaverse may be a bit of a stretch but the idea of transposing a physical world into a digital space and carry out activities in that space has some of the characteristics that are associated with a metaverse.
- Replika overcomes the barrier of time, rendering the voice, experience and character of a person that may already be dead supporting interaction with a virtual replica that can be met in the cyberspace. This service has some characteristics that place it into the metaverse: the presence of autonomous avatars that can interact with digital copies of real people beyond the constraints of space and time.

- Immersive gaming, leveraging on virtual reality, populated by avatar of real people (players) and with their own digital characters are also part of these proto-metaverses.
- Virtual spaces have been created by industry, and are being used, for training purposes, for collaborative working, for simulation and more. As an example, the Cave, by Reply, supports remote collaboration and the mix of physical equipment with digital ones (through their mirroring via digital twins). That environment can be applied beyond the shop floor of a factory, as an example to create a virtual environment, a metaverse, for patients to overcome certain types of disabilities.

These are just a few examples to show that there is a continuum from the physical space to the metaverse and we have already moved the first steps.

Metaverse(s) characteristics



The Metaverse (in dark blue) is becoming part of our life. It is going to become bigger (pale blue) in the coming years, as more and more of our life will be "lived" in the metaverse. As shown, the Metaverse is initially flanking our life in the physical space. In the long term it will merge as the boundaries between the two fade away from perception. Around the metaverse I have placed the labels of characteristics that are needed for a fully exploitable -and livable- metaverse.

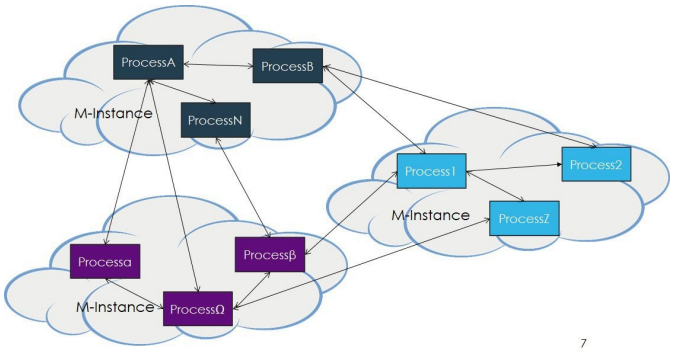
If the ones discussed in the previous post had some characteristics of a metaverse, to the point of being proto-metaverses, in the last two – three years we have seen the rise of spaces (and applications) that are much more in line with the present idea of a metaverse:

• Synchronicity: a "true" metaverse has to be synchronous with the physical world to create a seamless and coherent experience (e.g. if a company has gone out of business that should be reflected in the metaverse, if a family has moved from a city to another that should also be reflected in the metaverse. Notice that this does not imply necessarily that the metaverse is a "replica" of the physical space, it can still, and most likely will, have plenty of imaginary situations, however coherence needs to be ensured for all those aspects that are relevant). Notice, additionally, that this implies the metaverse to keep "living" - i.e. experience the passing of time- even when you are not "in it". Once you step back, you'll experience changes due to the time passing. It does not freeze when you are not there – you cannot pause nor reset. It is not like a video game that just stay put when you quit and then resume from that point when you come back. In this sense Land of Empires is not a full-fledged metaverse.

- Persistence: the past cannot be changed, like in real life. You can experience the present (getting different sort of experiences depending on who you are, how you are accessing and where you are in the digital space) and you can,

you actually will, condition the future by your presence and your actions. Once you act that becomes part of the past and can't be changed. Your actions affect the whole metaverse, of course to different degrees. In this sense, Zoom and other call conference services that are moving towards creating a virtual space for discussion don0t have the persistence characteristics. Once the call is over, … it is over. A conference call in the metaverse would be quite different since it will result in a change in the (local) metaverse) and people joining in a subsequent call will have all the memories of previous ones.

- Decentralised: there won't be a single master mind for the metaverse, there are going to be many metaverses in terms of ownership (different companies will create their own and then share it, thus making it part of the global experienceable metaverse). Work has started to provide standards to transform this decentralise patchwork into an homogeneous -from a perceptual standpoint- seamless and continuous metaverse. Technologies like blockchain play an essential role in this area. The Anitec Assinform working group on Metaverse, as a point in case, is the same one that looks on the blockchain application. The intrinsic decentralisation of the global metaverse is both a great upselling point and a big issue to be managed. A participant in the metaverse, as it happens in the physical world, can damage properties and other participants, unwillingly or maliciously. A sort of software "police" is required, as well as safeguards to ensure a trusted (trustable) space.
- Interoperable: From the intrinsic decentralisation of a metaverse it follows the need to make them interoperable (notice how this characteristic is basically excluding most of "current" metaverses from being a full-fledged metaverse, they are all centralised). This is addressed by the MPAI – Moving Picture Audio and Data Coding by Artificial Intelligence- Community (an offspring of the MPEG groups. The MPAI group approach to



The MPAI model to create standard for Metaverse interoperability. Image credit: MPAI

metaverse interoperability standardisation is to look at the functionality desired by the users, rather than attempting to define what a metaverse is -or should be. It is a very pragmatic approach that is appropriate with the current status of the metaverse, where we have no universal accepted definition and the concept is evolving rapidly. By focusing on standardising the functionality the group can provide the tools to let metaverse(s) developers to create their own patch and be sure that it will fit in the global quilt. On the left hand side the Metaverse reference model used by the community. The Metaverse FDC Initiative is connected to the MPAI work.

- Accessible: it goes without saying that the metaverse has to be accessible. The question is accessible to whom and how. Since the metaverse is to be

flanking our life and eventually provide a space to live that is a continuum across the physical and the digital spaces, it needs to be accessible to people, to all people avoiding any discrimination and barrier. This involves the means to access (devices: usability, affordability, …) and the way to interact (including language aspects, something that the current AI can cope with for a growing slate of languages). However, it should also be accessible to machines (software agents). The device "side" is likely to see a profound evolution. Whereas today the device is providing a point of contact with the digital world, in the coming years and decades it will be an entry point taking you "in the metaverse". Augmented reality and virtual reality mediated by devices will need to become seamless to make the metaverse a living presence. Ideally, a direct brain to metaverse connection should be the perfect link (although it can rise several other issues…).

- Immersive: new software, new devices and plenty of AI can create a sense of being part of the metaverse. Actually, the future might see a collapse of the metaverse on the physical space (or the other way round) with no perception of a dividing line. This is the idea of Metaverse explored by the IEEE FDC initiative where everyday life is lived in the metaverse, a fuzzy space mixing digital and physical.
- Platform for a flanking economy: finally, if the metaverse is part of the life space, it should also be an integral part of its economic aspects. It is obvious that one of the (strongest) motivation of industry in developing a metaverse is to reap economic benefit (both in terms of increased efficiency and in terms of increased revenue streams). Hence, we can bet that the evolution of the metaverse will go hand in hand with the evolution of what it means to do business in the digital space. This is likely to give a boost to NFT – Non Fungible Tokens-, cryptocurrency, blockchain … Notice how all of this goes well beyond the e-commerce of today.

Present metaverse(s)

In the IEEE FDC Metaverse Initiative we distinguish between the experience metaverses and the industrial metaverses. The former are created to provide a digital world where participants can interact to get an experience, like gaming, social gatherings, sharing the experience of arts (music, theatre, ..), sharing an experience of being in a shop, a mall, a realtor store …, the latter are created to work as a sort of digital shop-floor that can be shared by different parties to create a product. These latter are much more structured than the former. On the

The Sandbox is one of today's metaverses, allowing participants to create their own world and interact with other participants. Image credit: The Sandbox

other hand, the former are usually supporting each single participant in the creation of his own space.

In the last years several metaverses have been built, like Fortnite that already in 2018 had some 3 billion $ in revenue in its Epic Games and Roblox that in 2021 reached a 39 B$ valuation in its IPO (current market cap is some 22+B$).

Among some of the newest "experience" metaverses you may be interested in:

- The Sandbox: it is a metaverse providing tools to let participants build, own, sell their virtual patch of land/resources like gaming, using the Ethereum blockchain. As more is being built the metaverse expands.
- Decentraland: it is similar to The Sandbox, also using the Ethereum blockchain. It is run by a decentralised autonomous organisation (hence the name), owned by its users, and has a significant number of followers, a few thousands on average present at any time, with peaks during events, like concerts. It is difficult, in the metaverse to tell real human users from bots roaming the metaverse…
- Axie Infinity: another metaverse using Ethereum blockchain, inspired by Japanese video games like Pokemon and Tamagochi. Characters in the metaverse are associated (identified) to NFTs – Non Fungible Tokens-. To enter Axie metaverse you need to have a digital wallet and open an Axie account.
- Sorare: this metaverse focusses on NFT-based fantasy football games. Participants can play and trade cards. It is expanding to include any sort of collectibles and again, participants play a role in its expansion.
- Illuvium: this metaverse offers an immersive role-play experience through avatars (called Illuvials). They exist as NFTs holding a value on an Ethereum blockchain. It is up to participants to "arm" their illuvial by buying weaponry and directing their behaviour in terms of strategy (since these illuvials are autonomous agents, you cannot control them as if they were puppets).
- Bloktopia: this metaverse combines virtual and augmented reality with blockchain. It describes itself as a 12 floors skyscraper representing 21 million bitcoins. Users become virtual landlords that can earn revenues through virtual land sales, advertisement, organisation of events that other users pay to attend …
- Sensorium Galaxy: this metaverse is still in the prototyping phase It is being created by artists with different areas focussing on music, dancing meditation. Each of these areas is world providing specific experiences to participants. Each of these "worlds" act as a hub and it is being expanded by participants.

As you can see I picked up a variety of current metaverses in the "experience" domain. They differ from one another but they all share the characteristics I mentioned in the previous post. They all require a "familiarity" with the gaming environment, with blockchain and NFT, something that exclude most lay people from participating.

They are also quite far from the general idea of a metaverse as a space where digital and physical overlap, or converge. They look more a sort of sophisticated digital spaces to experience specific activities, basically detached from the real life.

Palette of the main technologies needed for the metaverse.

Technology as the evolution fuel

There are, as it can be expected, plenty of technologies that (will) power the metaverse. The most crucial ones, as I see it -and looking forward your comments on this!- are:

- Augmented / Virtual Reality
- Artificial Intelligence – ML/Gen. AI
- Digital Twins
- Blockchain / NFT
- IoT
- 3D image management
- 5G / 6G
- Brain computer interfaces

Let's take a look.

Augmented / Virtual Reality

OK, let's state the obvious. AR and VR are essential technologies for the metaverse. Or not? Today's metaverses and the proto-metaverses of the past exist (existed) even without AR and VR. You could access Second Life from your PC and you can do the same thing with Decentraland and the others metaverses I mentioned in a previous post.

However, the availability of devices supporting AR and VR create a seamless experience that can attract more and more users. The market of AR and VR is expected to reach 8.2 billion $ in 2028 (in 2023 is estimated at 1.8 B$). What is most significant is the expected growth, a 34% year over year (CAGR). This means that the "feeling" of experts is towards the availability of some leaps in devices capabilities.

In terms of software -applications- we can expect advances in AR and VR as AI and 3D image management progress.

Virtual Reality can foster immersion in a metaverse, Augmented Reality can support a metaverse that is a fusion of the digital and physical world. Gaming is a clear target for VR device designer (and can also be very useful in industrial metaverses). Augmented Reality ont he other hand can be important in industrial metaverses, in collaborative environment, in education, retail and more. Some kind of gaming can also leverage on AR.

Some observers feel that the metaverse goes hand in hand with the evolution of AR and VR. Personally, I see the two as co-evolving, benefitting from one another but at the same time the failing of one will not -necessarily- mean the failing of the other. The metaverse may not become a (the) life space in our future and we will still benefit and use AR and VR. Similarly, we might not get (within the next few years) breakthrough devices supporting AR/VR and yet we can see the idea of metaverse evolving and taking roots in ours lives.

Artificial Intelligence for the Metaverse

Artificial Intelligence is the powering force of the metaverse. The big issues are related to who will be controlling it and what type of control can actually be enforced. Image credit: Cointelegraph – The Future of Money

Artificial Intelligence is evolving so fast that it is difficult to keep track. It is not just evolving in terms of capability but, possibly even more important, in terms of:

- tools to create AI, with the effort (and cost!) of training Ai through LLM -Large Language Model- plummeting from million $ to hundreds of $ (a decline 50 times faster than the Moore's Law) for specific application domain, whilst the cost of creating LLMs keeps rising (expected to rise from today's 100 million $ to 500 million $ in 2030). Notice how this parallel decrease-increase is on the one hand fueling application and creating oligopolies in the control of AI. These latter may be counteracted by the rising wave of open AI platforms (not to be confused with OpenAI that started as open software and it is now a very closed software designed to make money).
- application domains, where we are seeing a pervasive AI in more and more fields. In a few years it will be difficult to find a single business areas that could operate without using AI to a certain extent.

In spite of the many interpretation of what a Metaverse is, or should be, there is a strong consensus that AI is an essential technology that permeates any metaverse in every aspects:

- creation
- operation
- fruition from users

- leverage (business value)

Out of the many nuances of AI the three main technology areas that I see crucial for the Metaverse are:

- Machine Learning
- Generative AI
- Chatbots

Machine Learning will be essential for a persistent metaverse, that not just keeps track of what "happened" but also learnt and keeps adapting. It should be applied both locally (to serve specific interaction, like between two avatars/digital twins that have to remember what they learnt through interaction) and globally, to evolve the whole context where it makes sense (keeping the two aspects, local vs global, distinct, as it happens in real life, with the possibility for the use to understand clearly what is local and what has a global impact (i.e. managing of privacy issue in the metaverse).

Generative AI will play a crucial role in providing tools for creating metaverse landscape, virtual characters or impersonators. Furthermore it can be used in dialogues based on natural language and in simulation of reality.

An important contribution to the metaverse will be given by chatbots, giving voice to virtual characters, to objects and acting as gateway in natural language for participants at the edge of the metaverse (you and me discussing with "something" in the metaverse. Most likely they will be powering the natural language interface of personal digital twin in their role of assistant.

Digital Twins

Businesswoman in VR glasses and her twin are interacting in the metaverse.. Digital Twins are an essential technology for the metaverse. Image credit: RTInsights

The metaverse mirrors, up to a point, the physical space. many objects in the metaverse are mirroring physical entities (in a broad sense to include abstract entities, like a city or a manufacturing process). This mirroring element is well represented by a digital twin. If what is mirrored is a person, we call that digital twin a "personal digital twin".

Digital twins technology is an important one in the creation and "operation" of the (a) metaverse. It both creates a link between the physical entity and the (digital) one inhabiting the metaverse (synchronicity) as well as

acting as a proxy of the physical entity (an avatar).

A Personal digital twin -PDT-will be a tool allowing a person to "live" in the metaverse through a proxy, both guided step by step and as a delegate.

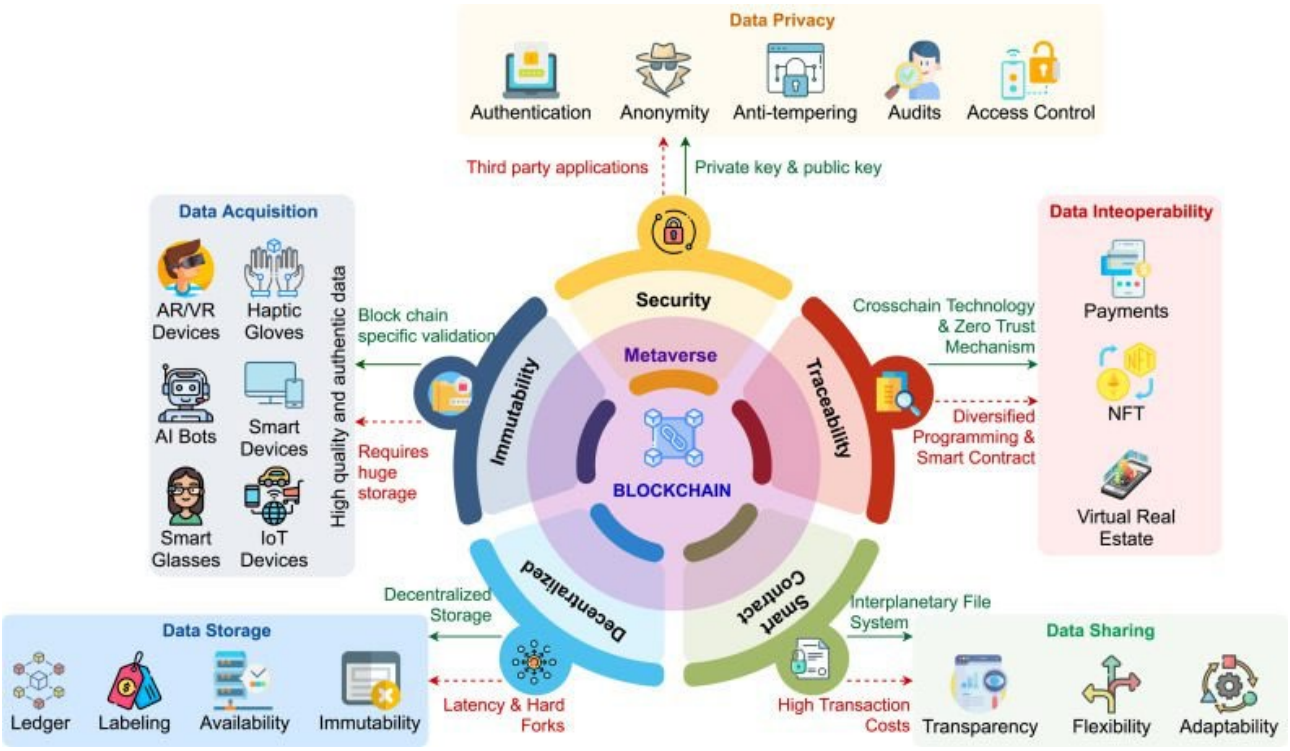
Interestingly, as there can be several metaverses of interest to you, you can have your personal digital twin roaming them all. In each of them it can show a part of your "personality", such as the one roaming the industrial metaverse of your company will be showing your working expertise, whilst the one inhabiting a mall metaverse will be more inclined to express your shopping interest… Even though each of them will exhibit different "sides" of you, they will need to reconcile all of them into your full fledged Personal Digital Twin. This requires an interoperability across several metaverses, something that is pursued by the MPAI initiative.

In the case of having your PDT in an experience metaverse (one you are inhabiting for social, entertainment, tourism, shopping, … i.e. personal reasons) the software executing your PDT and the data owned by your PDT can be contained in your personal device, like your smartphone or your goggles (apart from any backup you can have in a cloud). The "executable instance" (you'll need one for each metaverse) can be run on the metaverse platform and will need to reconcile the data with your owned PDT master-copy.

In case of an industrial metaverse where your PDT is still owned by you but it is used by your company (or the client you have agreed to "rent" your PDT), the PDT instance will be managed by the industrial platform executing that metaverse. This is the case of a Cognitive Digital Twin -CDT-that has the "knowledge" and experience/skills that you have and that is being used in that industrial metaverse to contribute to the building of a product/service.

This area is still subject to research and there are several open issues related to ownership, control, accountability and responsibility. The guiding principle should remain that the ultimate accountability and responsibility is on the one making use of the CDT, but there should be mechanisms to certify the knowledge of the CDT (possibly along the lines of an English SAT certification). The aspect of knowledge ownership is even more difficult to frame since by executing your CDT on the metaverse platform you are both sharing your knowledge (and implicitly that sharing leads to other CDTs, including the one of the Company that will be orchestrating the process and CDTs cooperation) and learning new skills through the interaction with other CDTs. This is quite similar to what happens in the physical space where as you are performing some activities you are getting experience from the very execution of those activities as well as from interaction with other participants in the project.

The only difference, by no means a minor one, is that once a CDT has embedded Machine Learning capabilities its knowledge acquisition from interactions will be instantaneous and it will not "forget". A side issue will be how to transfer that acquired knowledge to you, the owner of that CDT. It is most likely that as this technology



A comprehensive representation of the role played by blockchain in the metaverse. Image credit: Thien Huynh-The et al, Blockchain for the metaverse, Elsevier

becomes more and more powerful the CDT of a person will drift over time and become more knowledgeable than the physical entity it mirrors. This, in a way is similar to today's situation where the applications we are using on our computers "know" more than we do. We know how to use them but we do not know how they are able to convert our instructions into a specific execution.

In turns this divergence raises further issues on accountability and responsibility. We are entering into an unchartered space.

I think the Digital Twin technology, already a reality in manufacturing, construction, healthcare and more will keep expanding and we will have our Personal Digital Twin well before the end of this decade. The Metaverse will be both leverage on this technology and possibly foster the adoption of PDTs. What is not clear is who will be leading in this area and if the PDT will be under the control of its physical twin, the person, or if it will be supplied to people by third parties. Also, it is most likely that in the coming years we will have more PDTs (each provided by a different company/service provider, like one for healthcare, one for shopping …) and only later in this decade they will be aggregated into a single PDT.

Blockchain/NFT

As pointed out, one of the characteristics of a metaverse is the decentralisation and another is to be a platform sustaining economic transactions. For both of these, distributed ledger technologies are an important tool.

Blockchain and Non Funginble Tokens -NFT- are obvious choice as technology to support both the decentralised management and the identity integrity of any object in a metaverse. Basically. a blockchain is a ledger keeping track of all objects and all transactions affecting any object.

One well known application is in the domain of cryptocurrency (that can also be used in a metaverse) but more generally a blockchain can support accountability for any type of objects and related transactions.

NFT records the digital ownership of objects contained in a blockchain thus supports a digital economy in a metaverse.

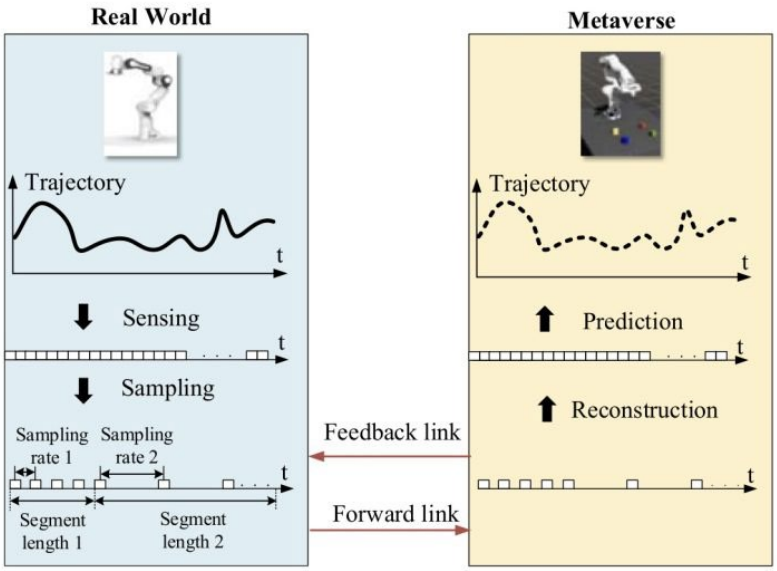
The graphic points out the many aspects of a metaverse that are making use of blockchain:

- Security
- Traceability
- Decentralisation
- Immutability
- Smart Contracts

For each of these areas the graphic explains the various services (functionalities) supported by the blockchain:

- Data Acquisition: as noticed, a metaverse is not a “static” space, rather it keeps evolving and part of this evolution is the result of data acquisition from its participants. As shown in the graphic there are several ways through which data area acquired. Each single data acquired enters into the blockchain and therefore becomes accountable.
- Data Storage: data are acquired, as noted, from different sources and the idea of creating a centralised storage presents too many issues (including ownership). Using the blockchain as a distributed storage system solve the problem. The consensus-based distributed ledger makes data more resistant to tampering and duplication. One issue, however, remains the latency in the propagation of a data throughout the whole metaverse since data needs to propagate throughout the entire chain.
- Data Sharing: the use of blockchain can ensure that data shared remain accountable, and do not change in the process. This is very important given the decentralised structure of the metaverse that by itself could easily lead to small local changes that propagate resulting in big changes. This is also a guarantee to the data owner that her data integrity is not degraded through sharing. Although this is always important, it is particularly so in an industrial metaverse where data have to be shared among different participants in a collaborative working environment.

- Data Interoperability: the evolution of the Metaverse is surely going to happen through the appearance of many (focused) metaverses and most likely a single person will participate in several. At the same time, applications developed for a specific metaverse would benefit from becoming applicable to others. Hence, data interoperability becomes crucial. The MPAI Initiative aims at addressing this interoperability issue. Blockchain can add onto the physical interoperability aimed by MPAI (that is fostering a common language across metaverses) providing cross-chain interoperability.
- Data Privacy: as the Metaverse aims at becoming our "living space" connecting the physical and the digital world with an ever closer relation between the two, it is obvious the relevance of privacy that the very presence of a digital mirroring makes more fragile. Additionally. as the boundaries separating the digital from the physical fade away, any tampering on the digital will have a direct effect on the digital. The aspects of security have to be taken into account before the creation of a metaverse and throughout its operation. The adoption of blockchain provides the user with the ability to control her data, also applying public and private key encryption. The "control" aspect refers to the possibility for the user to decide who can use, and to what extent her data. This allows the preservation of privacy since only those data that are considered "shareable" will become visible, and only to the designated parties.



IoT provides the starting point for synchronising the metaverse digital and physical parts. Image credit: Petar Popovski, Editor in Chief of IEEE JSAC – COMSOC

IoT

The metaverse, whether you see it as a purely digital space "connected" in some ways to the physical space or as a merge of the two spaces needs to have some parts of it "synchronised" with the physical world and "aware" of what is going on in the physical world.

The industrial metaverse needs something more: to affect the physical world from the digital one. This may also be the case for some "experience" metaverse (beyond the obvious of participants in the metaverse that can be affected by their participation in activities in the metaverse -or just by observing what is going on).

The synchronisation can take place through IoT -Internet of Things- both as sensors (from the physical to the digital space) and as actuators (from the digital to the physical space).

The synchronisation requires some explanation. As shown in the picture there is an aspect of delay – how much time it takes from a change in the physical world to be intercepted in the digital one and how much time it takes for this change to spread around the digital space. Plus there is an aspect of accuracy, the sampling issue. How precise the mirroring needs to be.

The “sampling” directly connects to the IoT (signal processing and AI can refine the sampling increasing its accuracy), whilst the “delay” involves the communication infrastructure (beyond the sampling frequency).

Both accuracy and delay -latency- have to be gauged in terms of the use of the data. An acceptable sampling interval can be anywhere between a few microseconds to several hours. Accuracy, likewise, can be measured in millimetre or in kilometre … it really depends what you are after.

This broad range of acceptable “data” makes sense when looking at the use of those data in a silos, where everything is well defined. As soon as you are opening up the silos, as it can be the case in a metaverse, the situation gets more fuzzy and complex. What can be acceptable for a specific use of data may not be so in other context of use of that same data. Assessing the traffic on a bridge or evaluating the stability of the bridge may make use of the same sensors and the same data but their “characteristics” need to be quite different: in the case of traffic you want to have a sampling in minutes (probably), for stability analyses of daily data con be ok. On the other hand for traffic you just need to know how many vehicles are on a bridge at a given time, for stability you need to have accurate data on vibration, stress and deformation. These may be the same data that can help gauging the number of vehicle but the needed accuracy is different.

Hence IoT connecting the physical and digital space in the metaverse need to be characterised to derive the meaning of the data and its applicability to different context.

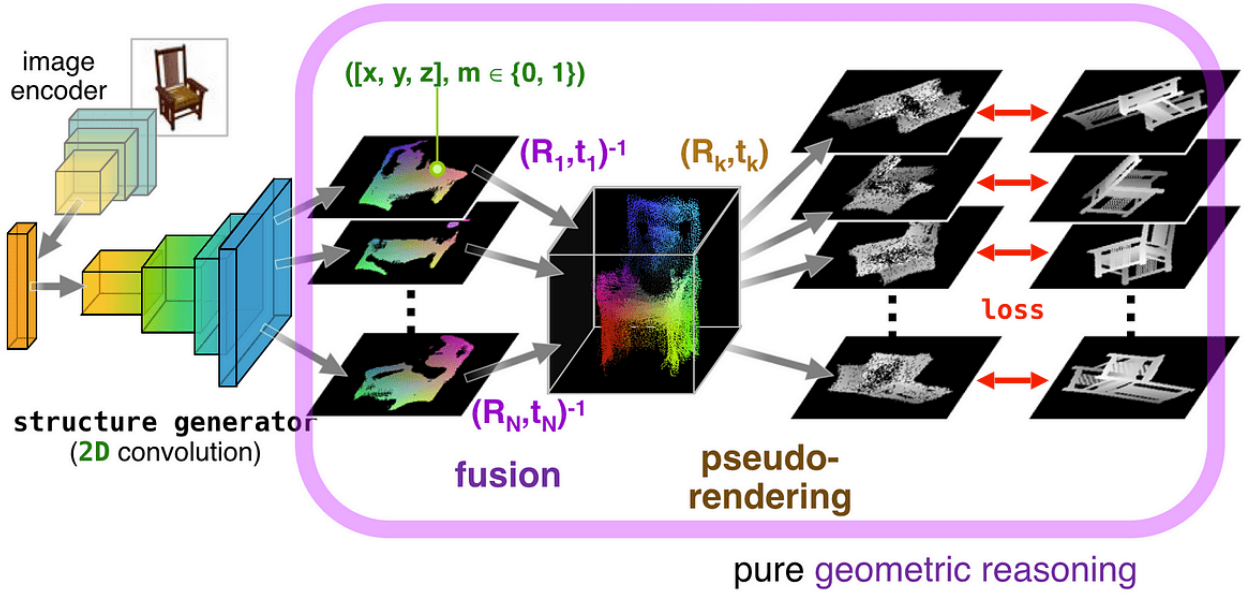
One way of attributing a characterisation to IoT is to connect them to Digital Twins. In this way IoTs are becoming the senses and actuators of a Digital Twin that has the capability to extract “semantics” from the data provided by its “senses”, also correlating them to the global environment and to insights derived from the interaction with other Digital Twins.

It is obvious, but worth mentioning, that data provided by (sent to) IoT need to be secured, hacking will be a major issue, the more so as the metaverse will be acquiring a value (both economic and social).

Another aspect worth mentioning is that today's IoTs are basically being deployed and used to serve a very specific purpose. There are billions of them and they keep growing to reach hundred of billions in the coming decades. However, these number may fool us, because of the siloed design. The metaverse, in principle, can turn the IoT world from siloed environments to a global mirroring of the physical world. This would be a major change.

In this line we should see the work going on in Gaia X (related to industrial application, healthcare, agriculture, …) to create data spaces and the work of the MPAI Initiative to foster metaverses interoperability.

3D Image Management



Schematic for creating a 3D model (and images) from a 2D image. Image credit: Phúc Lê, Vitalify Asia

We have been born in a 3D space (and our memories and expectations provide for the 4th dimension, time). Participating in a metaverse that can represent our living space and feel like a living space requires creating, operating and maintaining a 3D space similar to the one we are used.

For many years computers have struggled to create "credible" 3D spaces. Just think about 3D games: at a first glance you can say "this is an artefact!" The latest progress, particularly leveraging Generative AI, have changed the landscape. Now the question is: how can I tell an artefact from the real thing?

Artificial intelligence, indeed, is a crucial component in image creation and operation. It is only in the last few months that we have seen convincing results starting to appear in movies. The big difference between an image and a movie is the time

dimension. In a movie the relations among objects in an image change, and as they change light plays differently on each one. Our brain has evolved to pick up clues from the way light is reflected (and “assumes” that light comes from above, use and artificial lighting projecting from below and what was a bas-relief is now perceived as engraved).

We can also expect much better devices (goggles) to explore the landscape of the metaverse and software that provides the capability to walk around an object to see it from different viewpoints.

Part of the 3D image management technology relates to the creation of virtual objects that are perceived as replica of real objects. Several on line conference tools, such as Frame, provide the capability to animate avatar to represent participants in a call. If you had any experience with these avatars I am sure you got my same feeling on how very basic and “un-human” they look.

I should also note that in some cases, and for some people, having a crude mock up may be better than having something that looks exactly like the real thing. You might be, as an example, more at ease in participating in a virtual meeting in the metaverse with a character that does not look like you …

In an industrial metaverse there is. quite often, the need to distinguish between what is representing a real thing (a cog, an engine, …) from what is an idea, a specification of an object yet to be created. Hence, the need to have 3D image management addressing these different needs.

Part of this technology (that is actually a set of technologies) is the capability to transform a 2S image into a 3D virtual object, (as shown in the opening schematics). Other parts deal with the association of characteristics to a 3D image, like texture and softness, hardness. The use of haptic interfaces requires this characterisation of any object in the metaverse. It is also required to have credible interactions (you don’t expect to see a person walking through a wall -unless you are in fantasyland).

3D reconstruction of the Titanic, based on sonar signals. Image credit: Atlantic Productions / Magellan

A recent, amazing, example of a 3D image reconstruction of the Titanic based on sonar signals reconstructed by software to create 3D images of the ship sunk in 1912 and laying thousands of meters below the surface of the ocean, highlight the current capability of 3D imaging.

The association of characteristics and meaning to each object/entity in the metaverse is going to be crucial to its success. In an industrial metaverse you would expect that part of these

characteristics define how objects can relate to one another (can I place that axle in that cog?). Most CAD platforms provide ways to define and manage these characteristics.

I am pretty sure that in the coming years, particularly after we will have a leap in performance of 3D goggles, 3D management technologies will improve exponentially.

The IEEE Communication Society – COMSOC- is looking into application of 5G and 6G as the communication fabric for the Metaverse. Here is the banner for the course on this subject "5G, 6G, and the Metaverse: A Silicon Valley View". Image credit: COMSOC

5G/6G

A metaverse would be of no use, and to all purposes it will be non-existent, if you cannot access it. Communication to, from and within the metaverse(s) is crucial.

We accessed SecondLife using landline connectivity and, partly, 3G wireless system. Nowadays the access has to be wireless to ensure continuous "presence".

The high real life imaging that should characterise our experience requires high bandwidth, possibly in the order of 10 Mbps and up to 100Mbps in case of very dynamic landscape with plenty of action going on.

Also, low latency, in the 10 ms range, may be important if we are using immersive devices (VR goggles) since delays of 20ms and above would create a jagged flow of images.

4G may be ok in most situation, of course 5G availability would be better. You can take a look at the video below discussing 7 technologies for the Metaverse, I have discussed them in the previous posts, including 5G and 6G. It makes for a nice visual summary of this technology part.

Interestingly, 6G might offer capabilities that, along with the evolution of other technologies, and particularly of BCI – Brain Computer Interfaces that I will discuss next, will let people experience the metaverse as an extension of their brain. For this a very low latency time and high bandwidth is needed, something that should be provided by 6G.

However, we are really in the future talking about these possibilities. The cluster of technologies we have today (both available and affordable) can only support a proto-metaverse and for that 4G can work.

Brain Computer Interface

I left this technology for last because it is really in the future. True, we have some applications today but they are at an experimental stage and the equipment needed is for sure not seamless. Unless you have a very strong need for this you'd rather avoid it!

If this setting feels a bit scaring, think about having a surgeon implanting a chip in your brain … Image credit: Wunderman Thompson

If you imagine the metaverse as the new space where you live your everyday life, a space made up of physical and digital objects and experiences, all merged together forming a seamless continuum, you don't want to need a "device" to access it. Indeed, there should be no access whatsoever, as there is no need for a device to be in the physical space.

Your brain has to live, i.e. be seamlessly connected, to all aspects of the cyberspace, using the usual senses to connect with the physical space and some digital senses to connect to the digital space.

The "technological answer" to this is to be found in the Brain Computer Interface (or Brain to digital Interface).

So far we have three approaches to connecting our brain to … the web:

- using our senses as mediators, like when you are using VR goggles. In the future these "goggles" can shrink first to sort of normal glasses to stimulate visual sensation equipped with an earbud to stimulate aural sensation; then they can shrink further to be layered on the eye, electronic contact lenses, and further on to be implanted as a chip directly on the retina – we are really in the future- (always flanked with a smaller and smaller earbud to stimulate aural sensations). Along the same lines haptic interfaces can shrink from something we hold in our hand to gloves to electronic patches on our skin to provide tactile sensations. Movement sensation can be provided through advanced earbuds, although we are still far from overcoming dizziness.
- using external electrodes (see image) to capture the electrical activity in our brain and signal processing + AI software to make sense of that electrical activity, plus a set of actuators, electro-magnetic stimulators, to "steer" brain "thoughts" in a given direction, e.g to re-create images, sounds and more. It

should be noted that some progress is being made in the Brain to Computer direction whilst the opposite communications is still more a dream than reality (although some crude communications has been proved possible. Besides, so far, all communications from a computer to the brain has required implanted electrodes (see next point).

- using an implanted device -normally consisting of a network of sensors plus chip to analyse what is going on, communicate wirelessly with the external and stimulate the brain based on signals received from the external. There are a few companies, like Neuralink, exploring this avenue. Some results have already been achieved but the focus is on helping people with serious disabilities. The implant procedure requires surgery and we are still in the pre-experimentation phase on animals. This road is still long and winding, we do not know what to expect after the next bend. I personally feel most unlikely that even in the next decade we can see an application of embedded device in the brain for the purpose of connecting to the web for leisure.

The only approach I see as promising for this decade is the first one, where a mass market adoption of smart glasses can be foreseen within the next five years.

Industrial Metaverse

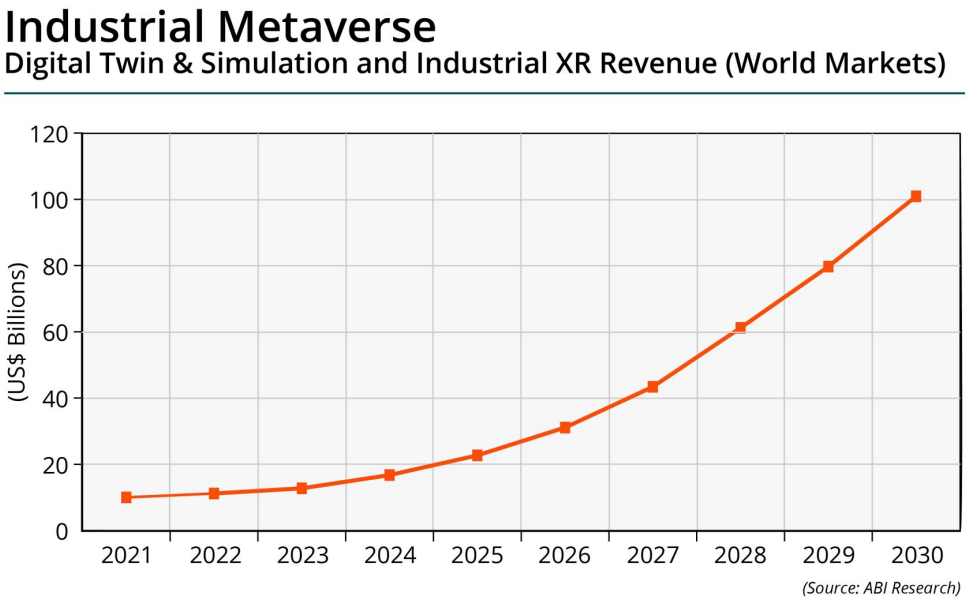
In this and following sections I will focus on the Industrial Metaverse, since it is the one I am exposed to both in the IEEE Metaverse Initiative and in a number of initiatives, including The Anitec Assinform Metaverse working group, in the EIT Manufacturing Industrial Metaverse activities and in the Gaia-X Data Spaces initiative.

Market forecast

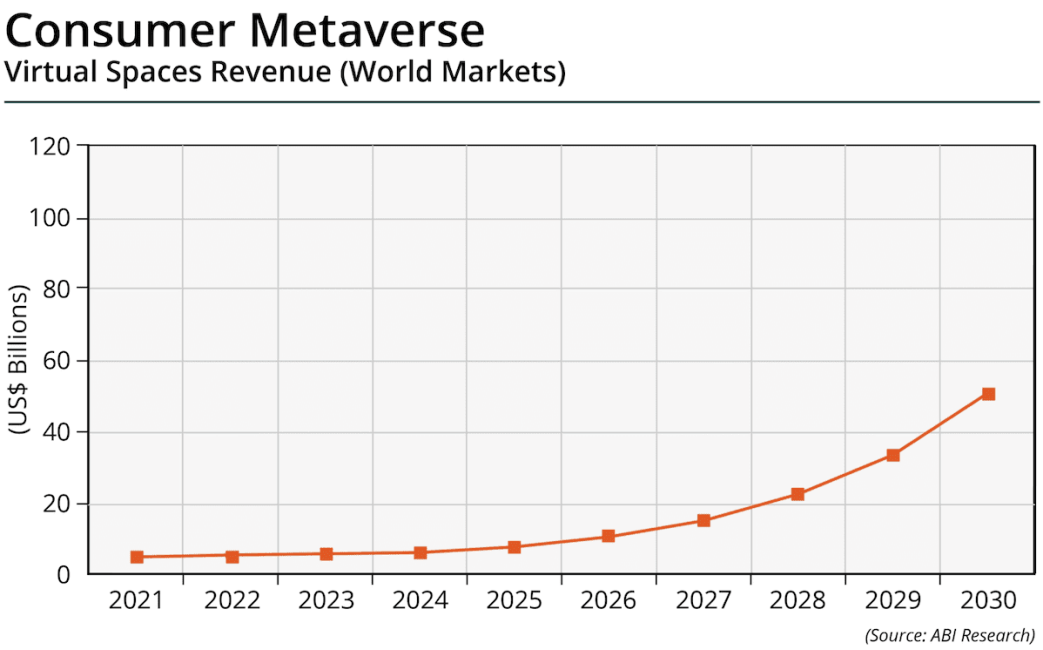
To many people the Industrial Metaverse might seem like poor relation of the Metaverse everybody is talking about (socialised by Meta) used in gaming, entertainment, …. As a matter of fact the Industrial Metaverse is the leading Metaverse because:

- it is an everyday, and growing, reality in several industry and industrial processes
- its market value exceeds the one of the “experience” (consumer) metaverse.
- its “fall out” will be affecting many people, not just the ones using it in an industrial environment to support design and manufacturing, but also the end users that will engage in the industrial metaverse to learn about the product

and, often, to use the product as some of its functionality will be available, experienced, through the digital space.



The expected market value of the Industrial Metaverse, including Digital Twin, Simulation Software and XR interfaces. As shown in the graphic the world market is expected to grow from 17B$ in 2023 to over 100 B$ in 2030. Image credit: ABI Research



Market value estimate for the Consumer Metaverse. It is around 5B$ in 2023 and it is expected to exceed 50 B$ by 2030. Image credit: ABI Research

The two graphics show the current and expected market value (worldwide) of the industrial and of the consumer metaverse. It is clear from the projection that the

Industrial Metaverse has the lead in generating market value and since innovation is affected by the perceived-forecasted market value it makes sense, at least to me, to consider the Industrial Metaverse. I am quite sure that its evolution will be steering the evolution of the Consumer metaverse.

We have seen in June 2023 the presentation of the much rumoured Apple goggles. They are supporting, in what seems a very nice way, both AR and VR. The tag price makes them more appealing to the professional market but we can expect price to decrease and make them affordable to an even broader audience.

An articulated discussion on why the Industrial Metaverse will eclipse the consumer one can be found here.

Key Points

The MIT in collaboration with Siemens has published recently a well structured report looking at the current status of the Industrial Metaverse and on its expected evolution. I will be using this report in my considerations on the Industrial Metaverse. Please be aware that all considerations are mine, I am not trying to attribute my thoughts to the report.

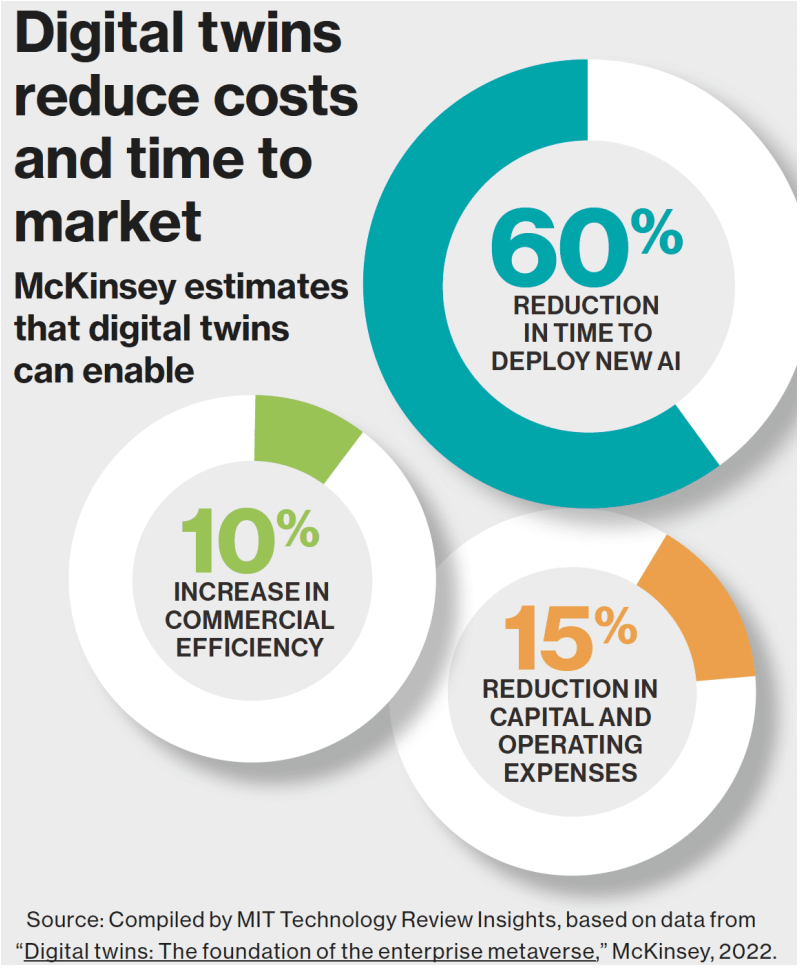
There are 6 key points emerging from the report (all considerations are mine):

- The Industrial Metaverse is bringing **together** the digital and the real world. The key here is the word "together". The Industrial Metaverse is not seen as a separated space from the real one, as it is often the case for the experience metaverse where you play a game in a fictional world, where killing is not having are impact on the physical space (although it might have in terms of culture and brain influence!). What goes on in the digital side is affecting the physical side, or it is going on to evaluate what to do in the physical space. Notice that, from an industrial point of view, a service shall be considered as an integral part of the physical space, even if it is implemented in software. In other words: whatever goes on in the Industrial Metaverse is meaningful for the company and ultimately for the end user.
- Digital Twins are a crucial building block of the industrial metaverse. Digital Twins have been used by industry for several years now. By far, today, they are "invisible", being a software package that gets data from the real world (and or the digital world) and behave in a way to mimic their physical counterparts (here again, let's keep in mind that the "physical" counterpart, its physical twin, can be made of atoms, bits or any mixture of those, like the digital twin of an organisation, or a cognitive digital twin embedding knowledge….). In the Industrial Metaverse these digital twins become visible to our eyes, what we see in the metaverse is a visual replica of what is being mimicked, like an engine. People working in the metaverse will be able, seamlessly, to move from the physical entity to the digital one created through the digital twin. In a way, digital twin in the metaverse will look much more real. As visual

representation improves (device, connectivity, …) people may lose track of the distinction between the digital and the physical "embodiment" of an entity.

- The Industrial Metaverse will transform all industries: on this point the report highlights how already today the use of digital twins has changed the industry in many of the product stages, from design to simulation to manufacturing through operation. The increased role of digital twins will impact even more all the stages (including the flanking of services to a product) and this will change the industry, its business model and its organisation.
- The Industrial Metaverse impact will go beyond industry, affecting and changing our everyday life. The expectation is both the Industrial Metaverse will stimulate development of better interfaces (devices to access the metaverse), better software and functionality to interact and "live in" the metaverse, and a growing number of products will be existing in the metaverse, meaning that end users to get the full slate of functionality of a product will need to use it in the metaverse.
- The industrial Metaverse is still work in progress, with key capabilities and ecosystems still to be seen. The report is listing a number of areas, including connectivity, computational power, digital twin fidelity, interoperability, privacy, security, marketplaces, payment systems, regulatory frameworks that will keep evolving in the coming years. These evolutions are bound to keep redefining what a metaverse is.
- Cross-industry collaboration is essential. In spite of the existence today of some leading player that is defining a concrete implementation of a metaverse, the future will see a blooming of metaverses, some will end up converging, some will just fade away. This will be true for both Industrial Metaverses and all the other flavours, but for the Industrial metaverses there will be a strong push towards standardisation and for this cross-industry cooperation is essential. Besides, an industrial metaverse will require the participation of many players, suppliers and customers and most likely also of competitors.

The Internet of Twins



Digital Twins are the foundation of the Industrial Metaverse. In this graphic a synthetic view of the advantages expected by applying digital twins: 10% increase in commercial efficiency, 15% reduction in capital cost and operating expenses and 60% reduction in time to deploynew AI. Image credit: Digital Twins: the foundation of the industrial metaverse, McKinsey 2022

As previously pointed out when discussing the most important technologies that are/will support the metaverse, Digital Twins are considered a crucial one, particularly so in the Industrial Metaverse. The good news is that Digital Twins have been a reality in industry for a number of years. According to market analyses their market value is around 7B$ today (Allied Market Research: 6.5B$ in 2021, Markets and Markets: 6.9B$ in 2022) and it is going to exceed 100B$ by 2030 (Allied Market Research: 125.7B$ in 2030, Markets and Markets: 73.5B$ in 2027). These figures reflect their growing use in the industrial sector (that includes manufacturing, healthcare, constructions and more).

In the industrial metaverse digital twins will operate at all stages:

- as virtual mockup to test design ideas, support collaborative design (they are not mirroring any existing entity).
- as model of an existing entity, used to simulate in the digital space its behaviour, although they are not connected to the physical entity, hence what may be going on in the metaverse may not correspond to what is going on in the physical space. This can support what if analyses and collaborative solution search.
- as mirrors of what is currently happening in the physical world. This can be used to monitor and raise red flags. What if scenarios can be run in the metaverse using digital twins at stage 5. Also, digital twins at this stage 3, can be used to provide data and information to monitor quality, usage and lead to fine tuning of the production processes.

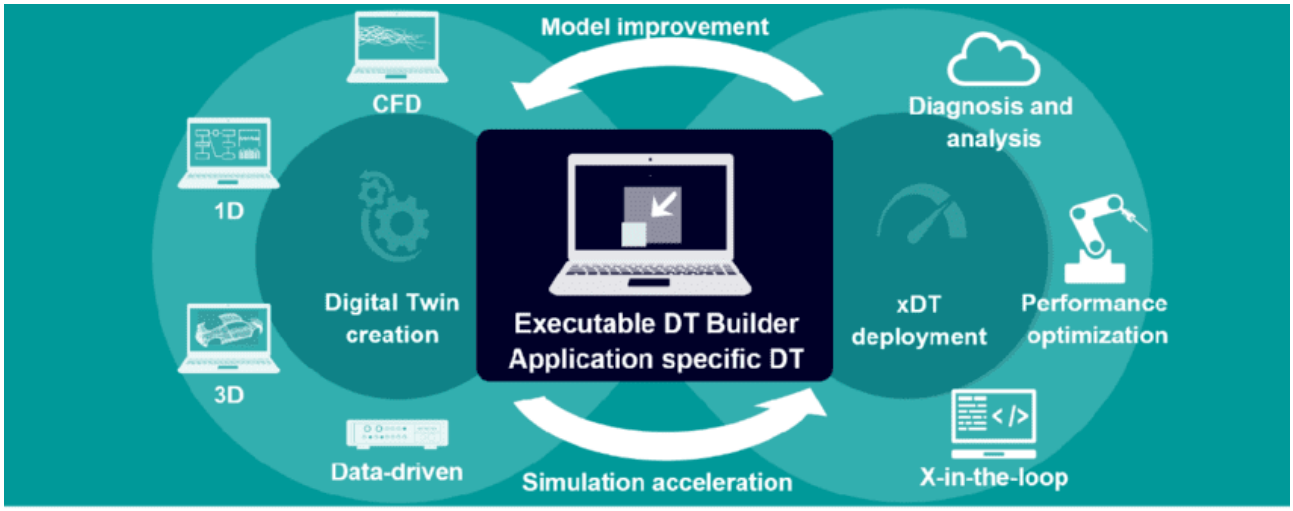
- as flanking entities to provide end users with additional functionalities through the metaverse. As an example, add on services can be provided through the metaverse. A wearable can have its corresponding digital twin in the metaverse. This can be intergated (interact in a closed space) with the person digital twin. By analysing physiological data partly derived from the “wearable” digital twin and partly form other “intelligence” available in the metaverse the person can receive warning and advice, offered as services. This is an example of an Industry 4.0 where a product is flanked by a service and the company that manufactured the product enters into the service delivery space.
- as an autonomous agent, still connected to an entity in the physical space but with an embedded intelligence and autonomous seeking goals. There might also be digital twins at this stage that are agents in the metaverse and do not have a physical counterpart. They influence physical entities by interacting with those entities ’digital twins. An example of application can be a model of virtual processes for a manufacturing plant that can allow the design and re-design of manufacturing processes, based on data received from one or more plants. By operating in the metaverse, rather than just being software packages, these digital twins become visible as virtual entities to engineers, suppliers, organisation planners … that can interct with them as if they were physical entities but with all the convenience (speed and low cost) of data.

Sometimes I struggle to grasp the difference between a digital twin, as we know and use it today, and one becoming part of a metaverse. Then I go back to an experience I had many years ago at the MIT Media Lab Tangible Media Group (still there!). Prof. Hiroshi Ishii showed me a large container on a table, some 2 square meter in size, filled with sand. On a side there were wooden blocks of different shape and colour. Some of these blocks represented a piece of a wireless telecommunication network, others represented buildings, forests … You picked up a block, like one representing an antenna, and placed it on the sand. Immediately you could see projected on the sand the coverage of the field emitted by the antenna as coloured light on the sand. The closer to the antenna the higher the field power. Then you placed a few blocks representing building and you immediately saw how the propagation was affected… In a way you could design your network by using your hands, blocks and sand.

In a way this could be used as an example of a metaverse, the only difference being that you are manipulating bits not atoms but the feeling should be similar.

Executable Digital Twins

The crucial characteristics for Digital Twins to operate in the Metaverse (and becoming useful) is to be executable. These executable Digital Twins are referred to by Siemens as xDT.



Graphic representation of the link between the creation of a Digital Twin and its use as an executable Digital Twin – xDT. Image credit: Dirk Hartmann, Research Gate

An xDT goes a step beyond a normal DT in that it embeds a grain of intelligence. It receives data from a number of sensors and integrate -makes sense- out of these data to the point that the data resulting from its processing can be considered as data by another xDT provided by a virtual sensor. Siemens considers these xDT as DT on a chip to emphasise their encapsulation and the possibility of composing higher level structures from by combining more elemental ones. Their flexibility and the display of an autonomous “life” make them an ideal element in the metaverse.

Siemens announced last year the signature of a contract with the Egyptian Ministry of Transport to create a fast speed rail system, 3 lines covering 2,000 km, East to West and North to South. The design of the system will be using Digital Twin and xDTs will be used to connect design plans to implementation. Up to 300 among engineers and staff will be using these xDT to get guidance, generate automatic reports, identify and track technical changes, monitor the implementation and identify errors before they can have an impact.

Unilever is using xDTs to support agile manufacturing. Based on a Siemens platform xDTs can mimic the new shapes of bottle used for a new line of product. Whereas in the past this required the set up of a manufacturing line to produce the bottles and test them, now all the bottles are manufactured, virtually, in the metaverse where designers can evaluate them, along with several customers, and engineers can assess the modification required in the production plant for their manufacturing and bottling. This cuts cost (changing a production line is a very costly endeavour) as well as dramatically decrease the time it takes to identify a solution and implement it.

Another example of use of xDT in a metaverse is the one od the Dubai Expo. Siemens has developed the operation and control of some 130 buildings that made up the expo site. Over 200,000 sensors collected data to feed a bunch of Digital Twins. Part of these Digital Twins doubled up serving as “characters” in the metaverse allowing visitors, through an app, to get a real time virtual experience of the Expo, and for people on site the xDTs provided the support for an augmented reality experience.

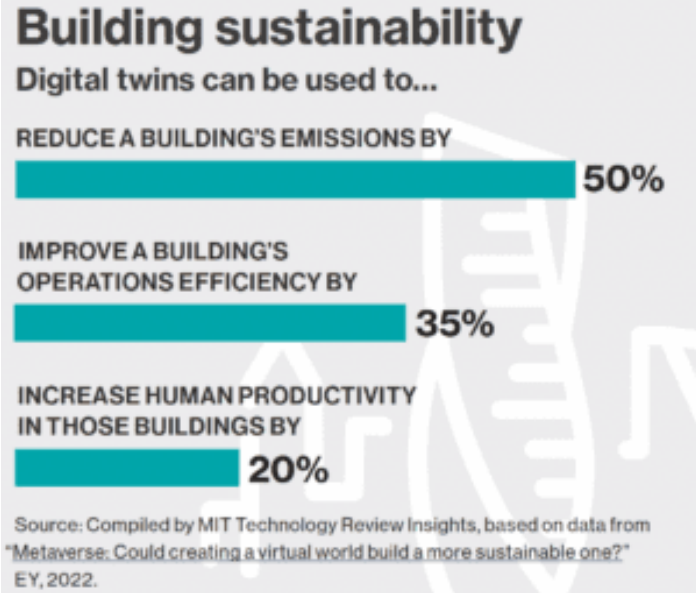
Executable Digital Twins for Siemesstadt Square

A crucial aspect, as I mentioned in a previous section, of an industrial metaverse is its usability by people. We already have plenty of tools that allows industry to do simulation, manufacturing with the support of software. You input a set of parameters, the software crunches numbers (actually this crunching is quite sophisticate... possibly beyond the capability of a person!) and it spills out results, in terms of drawings, tables, and even software that can be used by a robot in manufacturing.

Siemenstadt Square in Berlin: a project leveraging executable Digital Twins to create a urban space in the metaverse. Image credit: Siemens

The industrial metaverse brings the humans inside what goes on in the digital space. The visualisation, on the one hand, and the possibility of interacting with digital objects using your hands is what the metaverse is all about. Without the human participants there is no metaverse.

This can be applied well beyond industrial manufacturing. As an example, consider the Siemesstadt Square project. This project, ongoing, aims at



Expected efficiency gains deriving from the application of Digital Twins technology to a urban environment. Image credit: MIT, Technology

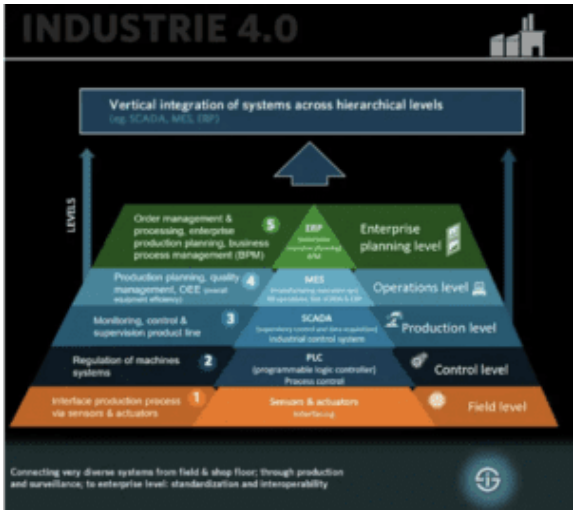
transforming 76 hectares of worn-out industrial area into a residential urban community in Berlin. The project has been designed from the start using digital twins. Several of these digital twins are transformed into executable digital twins that will support operations AND will become part of the metaverse for people to live in, both residents and people accessing the area for services, shopping or just strolling through it.

The metaverse will allow a complementary life in the digital space, overlaid on the physical space. Metaverse participants can experience this purely virtually (from anywhere in the world) using VR goggles or can experience both the physical and the digital on site using AR devices (like the announced Apple AR glasses).

I am using the Siemenstadt Square as an example because it shows some characteristics of an industrial metaverse:

- it comprises people and objects related with one another in a dynamic way forming a well-defined space
- it can be experiences purely as a virtual space, or/and
- it can be experienced on site as an overlapping of digital and physical
- it has a life (ongoing activities that keeps it changing) sustained by -executable- digital twins
- different (human) participants in the metaverse can experience -see- different things depending on their acknowledged role. As an example, maintenance crews at the Siemesstadt will "see" things that are not seen by the casual stroller, a resident might see something more than the casual stroller and something less than the maintenance worker. Also, the type of interactions possible will be dependent on the participant's role. A maintenance engineers may be able to activate certain actions, not permitted to other metaverse participants. Functionalities offered may also differ significantly. Again a qualified engineer can perform "visual" simulation of the potential evolution of a problem and what if analyses of countermeasures, something that is not available to other participants.

Fulfilling the Industry 4.0 Vision



The 5 layers of vertical integration in Industry 4.0. Notice at the bottom the goal on integrating the user layer. This is made possible through sensors in the product connected via networks to their digital twins and integrated in the factory digital space, aka its industrial metaverse. Image credit: HPE

One of the "vision" steering Industry 4.0 is the idea that all parts of the life cycle of a product (service) are connected one another and influence one another. This is represented by the vertical integration shown in the graphic, generated by Hewlett-Packard Enterprise solution. Notice, in particular, the role that the product will continue to have through its use (operation) on the other layers.

Basically, the whole life cycle is learning from the product usage (from the hundred of thousands of that type of product being used in different environment under different user demand): this can lead to fine tuning of the production to avoid issues, to selection of specific providers in the supply chain when a component proves to be better than the one provided by a different supplier, to change the specification of some components, to segment the delivery chain to address it with slightly modified version of the product better fitting specific usage, to create adaptation services, to improve the product in later releases, to design new products, to assist users when applying the product in specific environment and so on.

This becomes possible thanks to "data": the data generated through the use of the product, harvested by IoT embedded in the product or indirectly through interaction of the product with the environment that eventually creates feedback that is intercepted by the product manufacturer.

This plays along with the need to control the life cycle end-to-end, including reuse and recycle, an important factor to improve sustainability.

The fabric to sustain this interplay of the various layers is the industrial metaverse.

The metaverse, although reflecting a physical space, is not constrained by space-boundaries, all data (information) generated in a specific location can percolate through the metaverse instantaneously (as awareness, although their impact can be regulated by design, inserting time delay where needed).

The metaverse is more than a means to acquire data, it is the place to make these data visible and meaningful to different audiences (a same set on inter-related data can create different representation to convey meaning to different audiences: an engineer tasked with evaluating production quality requires/understand visual clues that are different from the one needed to increase awareness on the best use of a product to the end user).

Hence the industrial metaverse is more than a tool for a manufacturing company to streamline its production processes and collaborate in the digital space with its suppliers. It becomes the place where clients become aware of the potential of those products and the setting for an ecosystem where independent companies increase the product value and user contribute to the continuous improvement of the product.

Working in the Metaverse

How will the metaverse change the manufacturing world? Image credit: Canadian Metalworking

In the previous section I remarked how the industrial metaverse is the fabric, or the space, to accommodate the whole life cycle.

What does this mean for each layer? Let's start with what for me (when discussing an industrial metaverse) is the core layer, the production layer.

In manufacturing "producing" means to create an object, i.e. to assemble atoms. The digital part is in support to this goal. We use software for design, simulation, monitor and control the various processes, and to provide support to people involved in the production process, among several other things.

Why would an industrial metaverse be any different from what has been done in the past twenty years?

The industrial metaverse, as I see it, and based on discussions we are having in the FDC Metaverse Initiative, is a continuum across atoms and bits, there is no, or there should not be, any dividing line/border separating the two spaces. This requires a re-thinking of the manufacturing processes. Notice that this is in line with the vision of a Digital Transformation that should not be the flanking of computers and software to current machinery and processes, rather it should lead to a re-thinking of the whole activities and processes.

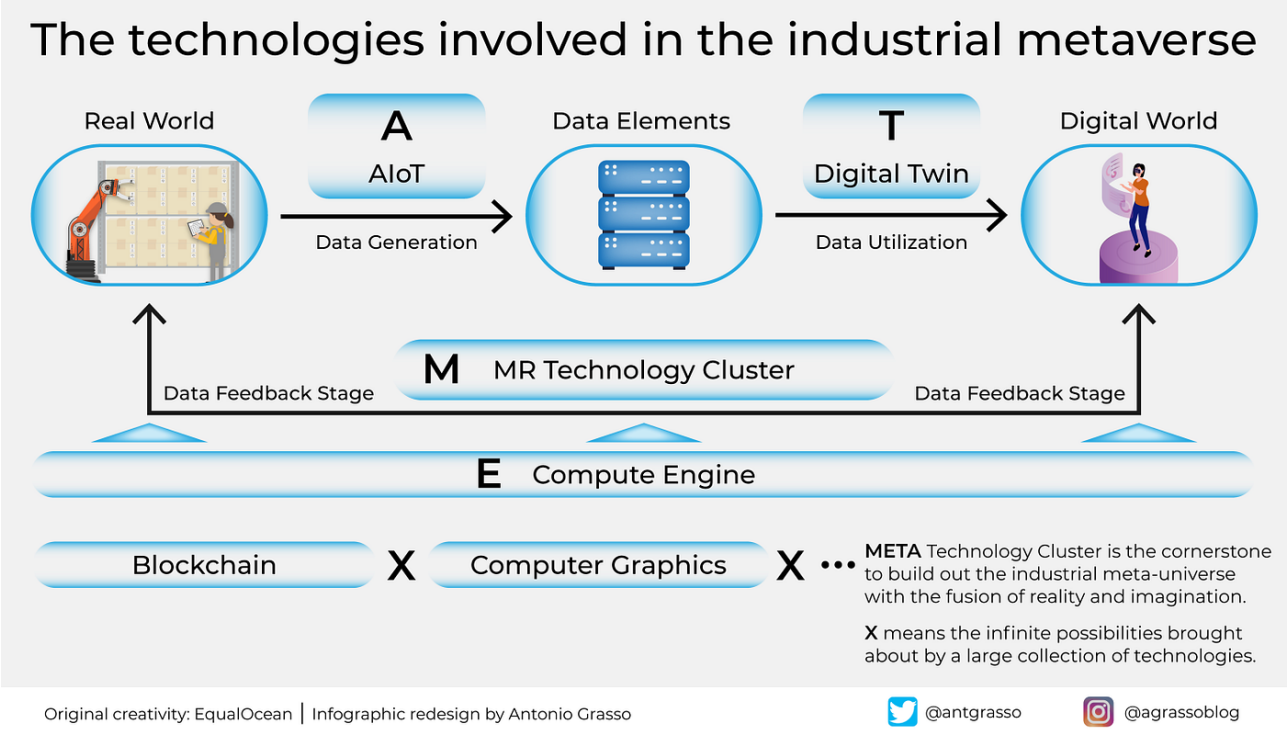
In this vision, all manufacturing takes place in the metaverse, and depending on what is needed the production processes may involve a physical tool, like a robot, a soft tool like a software package, a physical infrastructure like an assembly line, a soft infrastructure like a data space.

This, I feel, is the crucial point: manufacturing needs to be reshaped to fit the metaverse. Of course, you will seldom be in the position of a green-field situation when you start designing your manufacturing layer from scratch. Most likely you already have a plant with buildings, assembly lines docks to receive supply and to deliver finished products, warehouses and ... people. These latter are an important component of the manufacturing layer. As shown in the creative picture I have borrowed for this post, the people will find themselves immersed in a new

environment where bits and atoms are mixed and interaction takes place with both and through both.

The gap/differences between the "manufacturing as usual" and "manufacturing in the industrial metaverse may be significant, also depending on the sector. Drug production industry, as an example, has been moving step by step to an ambient that is quite close, if not already a well-defined, industrial metaverse, with scientists/researchers and engineers using VR goggles, haptic manipulators, extensive simulation with visual control in the design and testing of drugs. As real cases examples see:

- Nanome: The future of molecular design
- Virtual Drug Design
- In Silico discovery and data analyses



A schematic representation of the technology "families" needed and supporting the industrial metaverse. Notice how closely this ensemble resembles to the technologies used in the Digital Transformation transition and post transition with the addition of the MR -Mixed Reality- technologies. Also notice that only few years ago the data harvesting would have been driven by IoT, now we are starting to talk about AIoT, aka Artificial Intelligence IoT. Image credit: Antonio Grasso, EqualOcean

These are different examples of use of what might be called an industrial metaverse at the manufacturing layer. It shouldn't be difficult to translate this to a different field of manufacturing, like automotive.

The big challenge, facing industry, is design and orchestrate the transition.

Governing the Transition

As in most evolution from A to B the problem is not as much as what to do once you have transitioned to B, rather how to manage the transition.

A smooth transition is on everybody's agenda but reality is way more complex:

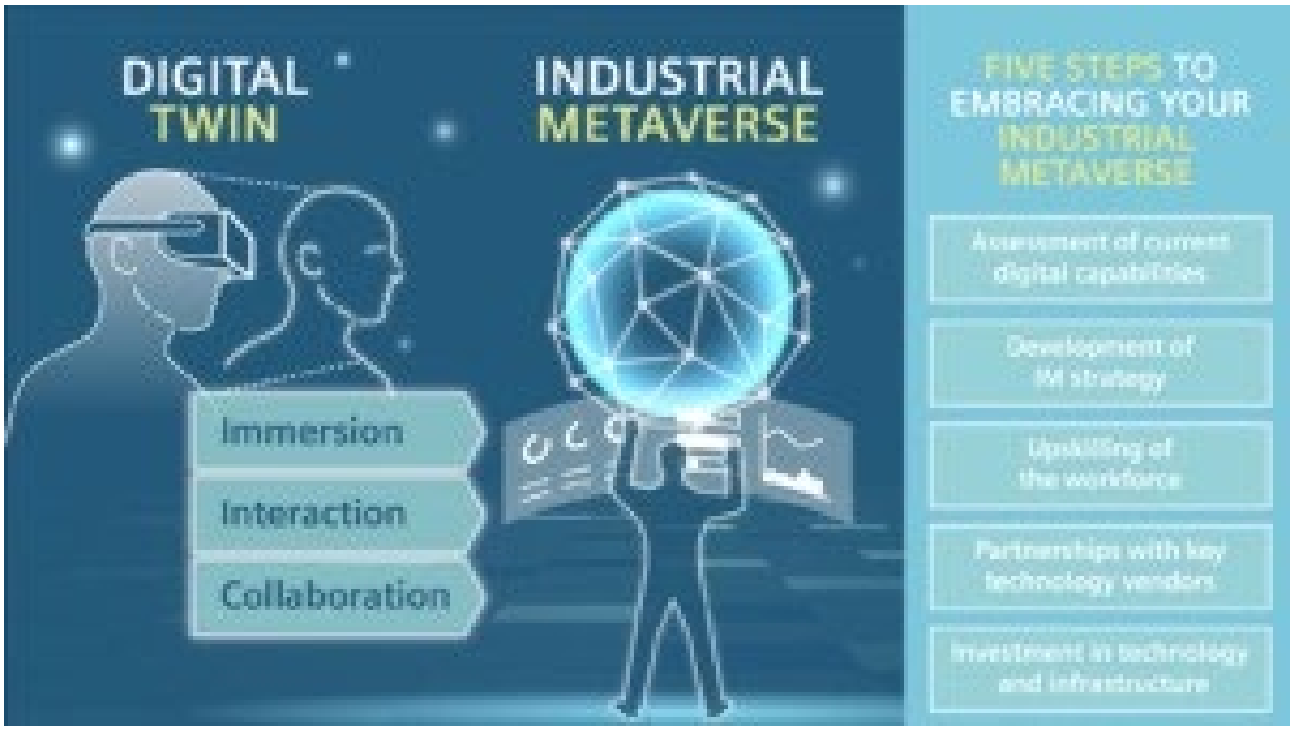
1. Decision stage
   - I am fine now, why should I transition to something that has yet to be proven?
   - I am facing problems right now, should I compound these problems with the ones of an unchartered path?
   - Should I wait a few months to see how the external/internal situation evolves?
   - Should I take the lead or just wait and see and them play the follower? I might be losing in head-start but I would gain from other experience.
   - What should I do with what I have today that won't be needed anymore once I transition?
2. OK, that's decided we need to get there. Now:
   - How can I evolve from the current situation? Disruption -mostly unfeasible-, or step by step?
   - What are the pieces of the target already available, what are the ones I need to build/acquire from scratch, what are the ones I have that need to be changed?
   - How should the transition be executed? Should I shift what I have to what I need to have, step by step? Should I set up a parallel operation in the new framework and once operational fade the current one out?
3. How will be "operation" in the new environment:
   - are new types of resources needed? Can these be found within the enterprise? Should new ones be acquired, in-sourced, activities out-sourced?
   - will there be new biz opportunities?
   - will there be a new ecosystem (providers, partners, ...)
   - are there regulatory issues, union issues, societal issues to be managed?
4. Socialise the change:
   - When? Once it is done; from the very start, communicate only the next step, communicate the "vision"
   - To whom? Internal resources; Partners; Value Chain, Customers; investors ...
   - Why? Marketing opportunity; create consensus; buy time

The purpose of the above list is not to be exhaustive, rather to highlight that a company embarking in a transition to an industrial metaverse is not going to be the same company at the end of the transition, exactly like a company that has undergone a Digital Transformation is a different company. It is no longer "biz as usual".

I already mentioned that there is quite a bit of overlapping between the Digital Transformation and the Industrial Metaverse. Basically the former paves the way to the latter.

You can have a company "using" the metaverse as a tool in some of its activities, like shifting to the metaverse for the design phase, or to engage potential customers and so on. In this case that company may not have executed a full bown digital transformation.

On the other hand, if a company has implemented a digital transformation making use of the metaverse will come as a seamless follow up.



Digital Twins can be the starting point to create an Industrial Metaverse and crucial players in the Metaverse operation. Image credit: Siemens

As shown in the figure, Digital Twins can be the starting point in the creation of the industrial metaverse. If you have executed a digital transformation as an industry you will have orchestrate ways to harvest data (through IoT), correlate and analyse them across various processes (possibly using AI) and create a digital mirror of your company as a whole (if you have been really ambitious) or of some significant portion of your resources, equipment, processes, ... In other words, you have created Digital Twins.

To create and "operate" in the industrial metaverse you have to make your Digital Twins "visible". They have to become visible characters in the metaverse. Notice that when I am saying visible, I mean visible to "us", humans. Without human participation there is no metaverse. So when looking at the figure you see the words "immersion, interaction and collaboration" associated to Digital Twins. They stand for the

capability to provide an immersive feeling to humans, to interact with humans and to collaborate with humans.

Siemens is delivering several of their manufacturing equipment with an associated Digital Twin and through the Mindsphere platform it provides a way to manage them. In an article it describes the steps suggested to use this as a starting point to create an industrial metaverse:

1. Assess present company digital capabilities
2. Develop a strategy for that company industrial metaverse
3. Upskill the workforce
4. Build partnership with key technology providers
5. Invest in technology and infrastructure

and presents three concrete cases:

- Coca Cola HBC
- General Motors
- Automotive AOMs

I suggest you take a look at these since they go beyond presenting what they have to discuss where they could go from there.

Obviously, Siemens is a "provider" so it is inclined to suggest that a company should invest in technology and infrastructure. I am not saying that this is not important, what I would like to point out is that in most cases companies may already have the required technology (or most of it) but are missing the vision of what to do with what they already have and the capability to use it.

As an example, most companies already have plenty of data, plenty of sensors and a communication infrastructure that can take those data from the originating points to the place where they can be processed and most important, they usually don't have the mechanism to actuate on those data, outside of the silos where they have been generated.

To move to the metaverse construction the missing part is the creation of a visual environment and the embodiment of digital twins to become visible "objects" in the metaverse. An obvious choice would be to have each digital twin looking like its physical counterpart, if one exist. Then the next step is to craft the set of interactions between humans accessing (immersing in) the metaverse and the various objects,

including digital twins, that populate it. This crafting should include aspects like authentication, permission and permanent effect of an interaction. Ideally, exceptions always possible if needed, an interaction with a digital character in the metaverse should lead to the same response one would elicit through the same interaction with its physical counterpart.

3D rendering of digital twins of wind-turbine, supported by MS Azure platform. Here the representation is displayed on a normal 2D screen but the rendering is made in a way that can support the display of those digital twin in a metaverse where an engineer could walk around the physical location -virtually, and inspect the turbine. Since in the metaverse anything is possible -as far as it does not distort the physical reality under observation, that engineer could walk on the sea water if that turbine happens to be located off-shore. Image credit: MS

You want to create a metaverse where the digital part:

- exactly mirrors your physical world so that decisions taken on the bases of what goes on in that space can apply seamlessly, and meaningfully, to the physical space

- enables you to do things that would be costly, lengthy and possibly not recoverable, in the physical space. As an example you might look at a turbine in the metaverse and suspend its connection to the physical space to test some what if scenarios, like testing how a wind turbine would react to gale force wind (at that specific location) if you keep it spinning. It can break down but that's not a problem in the digital space, you may try to go for lower spinning and find a good compromise to keep it working yet surviving the gale. Once this is found you can re-synch the turbine xDT with its physical counterpart and have it instruct the physical turbine to keep going with a new setting.

- can exist in different frames, each one specific to a participant in the metaverse. An engineer can both have a view and engage in certain interactions with some components in the metaverse and not with others, and a different engineer may have different authorisations. This may change the visual representation depending on who is viewing and why is viewing. At the same time the metaverse can support collaboration among participants, hence an orchestration of the different frames is needed. Standards like the one pursued by MPAI are essential in this respect and the platform supporting the industrial metaverse can accommodate all these requirements.

The concept of authorisation and frames is crucial in an industrial (and enterprise) metaverse, may be less so in a consumer metaverse.

The orchestration of the metaverse, providing rules, frames, … is an important part of the transition. The temptation for a company, particularly for those in charge of the processes, might be to translate current processes into the rules encapsulated

in the metaverse. However, this might not be a good solution, in general, like the drive to replicate in the new company resulting from a digital transformation the rules that applied to the company before the digital transformation. The danger, here and in the digital transformation, is to create un-necessary constraints that diminish, if not obliterate, the advantages that can bring operating in the metaverse.

The general advice is to re-think the company from scratch, build the company from grass root in the metaverse. This should be done before initiating the transition. The new defined processes become a target, the transition has to manage the shift from the existing ones to the new ones.

Industrial Metaverse - Sustainability

Image captured from the talk of Siemens CEO on the promises of industrial metaverse to make industrial production more sustainable. Image credit: Siemens

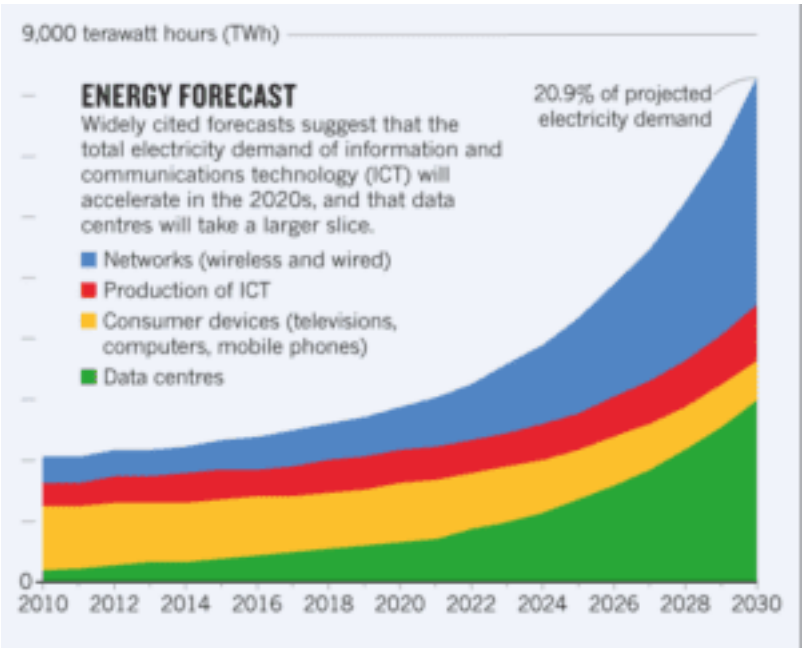
Industry is using 37% of the global energy, generates 20% of CO2 emission and recycle only 13% of its products material. This is not something to be proud... However, according to Cedrik Neike, CEO of Siemens Digital Industry, moving to the industrial metaverse can contribute significantly to increase industry sustainability.

The first obvious step in sustainability, measured in terms of increased efficiency (lower energy requirements, lower carbon emission, fewer waste, ...) can be obtained by executing the digital transformation. By shifting processes to the digital space you leverage on the lower "inertia" of bits: they are easier to move around, you can duplicate them at will at basically to cost in terms of raw materials, they are easy to discard (no waste!).

Taking the next step and moving into the industrial metaverse can further leverage on these plus points of digital.

With a true industrial metaverse the company, its resources, its people are operating in a symbiotic relationship across the digital and the physical space. Whether you are leveraging one or the other is partly due to constraints (if you have to deliver a coffee grinder you have to end up manufacturing it using steel, plastic ... whatever, bits are not good at grinding coffee beans!) but for the most part it is a matter of economics and social responsibility -ESG (Environmental, Societal and Governance).

The industrial metaverse is offering a company a lot of latitude in choosing the way to execute a given activity/process. You may want to take a look at the video by NVIDIA and Siemens on this topic (included below).



Bits are so "tiny" and weightless we often disregard their impact on energy. The he problem is that the amount of bits is staggering and the equipment needed to manage them is very power intensive. The graphic shows the expected increase in power usage in this decade to manage "bits". As you can see the lion share is taken by networks and by data centres. Image credit: Clarissa Garcia, AKCP

The use of smart digital twin (with embedded AI) is, according to Siemens, a game changer. A lot of effort is spent by industry in prototyping, trial and errors, reconfiguration of assembly lines, ... The use of a virtual factory to fully design and manufacture a virtual product can create, at very low resource consumption, the blueprint for the real thing. I have personally spoken with a company manufacturing insulating covers that took 2 years of finely tuning the production to cut waste from over 50% to less than 10%. This was done through the use of AI to analyse production data. Well, by stepping into the metaverse and using digital twins this same process could have taken a much shorter time and being done in the virtual space it would not have generated real waste, only virtual one. That means lower cost for the company and a more environmental friendly manufacturing process.

However, the landscape of an industry operating in the metaverse is not all rosy. Powering the metaverse will require massive amount of power that unless provided through clean sources will worsen the energy crises.

According to the MIT-Siemens report the Industrial Metaverse -IM- can support sustainability in various ways:

- The IM can assist in decreasing the use of physical resources by emulating them in the digital space and making use of them only at the very last moment. The mixture of emulation and 3D printing can dramatically cut the use of resources and decrease the production waste. This relates both to the product manufacturing and to the infrastructures (factory, warehouses) needed to support the manufacturing process. Also, the shift of manufacturing to the digital space for as long as it is feasible, makes it possible to decentralise manufacturing to places where it can be more environment friendly. This is

already the case for data centres that tend to be located where the climate is cooler (thus requiring less air conditioning) and where electrical power is available (thus cutting of power waste in transport and making use of on-site renewable sources). A further contribution can derive from the shift of product features and the flanking of services to products that can be managed and delivered in the metaverse. For this it is essential that the end customer becomes part of the same industrial metaverse (although using a different frame from the one used by the manufacturer). This goes hand in hand with the Digital Transformation and the shift to an economy of services - servitization. Notice, however, how the decrease use of resources affects those companies that have a business in the provisioning of these resources, from mining down to delivery. Decreased use of resources also means decrease revenues for some.

- The use of digital twins as proxy connecting the digital and the physical space through the life cycle of a product could support faster and smarter decision-making at any point of the life cycle when this is needed. A product can be constantly monitored for preventative maintenance, something that is less costly also in terms of sustainability than having to intervene after a problem arose. This is also leading to decreased waste. Notice, however, that this affects the value chain with companies providing maintenance services experiencing a decrease in activity/business/revenues.
- Innovation can shift almost completely to the digital part of the IM. Innovation is a costly endeavour, involving lots of trials and errors that generate waste of many kinds. By shifting the innovation process to the IM digital part industry can cut on these waste, save resources and speed up the innovation cycle. Notice, however, how faster innovation leads to shorter product life-time and henceforth to increased obsolescence and waste. Take as an example the cellphone market that showed a sale of 1.7+ billion cellphones in 2021. Since this is now a (almost) mature market most of these cellphone went to replace existing ones leading to an e-waste of 1.5+ billion cellphones. A significant portion of those replacement was motivated by innovation (and marketing, of course), as new captivating models hit the market. Stopping innovation is not good for business, and eventually not good for any of us who ultimately benefit from innovation, but it must go hand in hand with recycling and reusing. The IM, extending to all layers, as discussed previously, can become an essential force in making this happen.
- As already mentioned, the IM requires quite a lot of electrical power. It is essential to harvest this power form renewable, environment friendly sources. The good news is that part of the IM can be delocalised to take advantage of favourable energy source. A significant portion, however, remains close to the point of use, mostly "at the point of use". Powering million of devices to provide immersive feeling won't come cheap from a power budget, although we might expect significant progress in this area. It is crucial, however, to take the global view in this matter. Seeking localised saving at the expense of the whole is a mistake. We saw this happening in the telecommunication world. Till last century most of electrical power to use the telecom networks came from the Telco Operators who had their own (efficient) power plants. Then the advent of home routers, phone charges and the like

shifted the power consumption balance. Telecom Italia, to give an example, used at the end of the last century 2TWh (yearly) to provide their communication services and nothing more was required. Ten year later they were still using 2TWh of power but the whole power consumption ramped up to 6TWh, with 4TWh distributed among the end users who made -for sure- a much less efficient use of power.

Enabling the Industrial Metaverse

Although we already have several concrete examples of industrial Metaverse there is unanimous agreement that what we have is just a taste of what will be recognised in the future as a true Industrial Metaverse (same goes for the Consumer and Enterprise Metaverse).

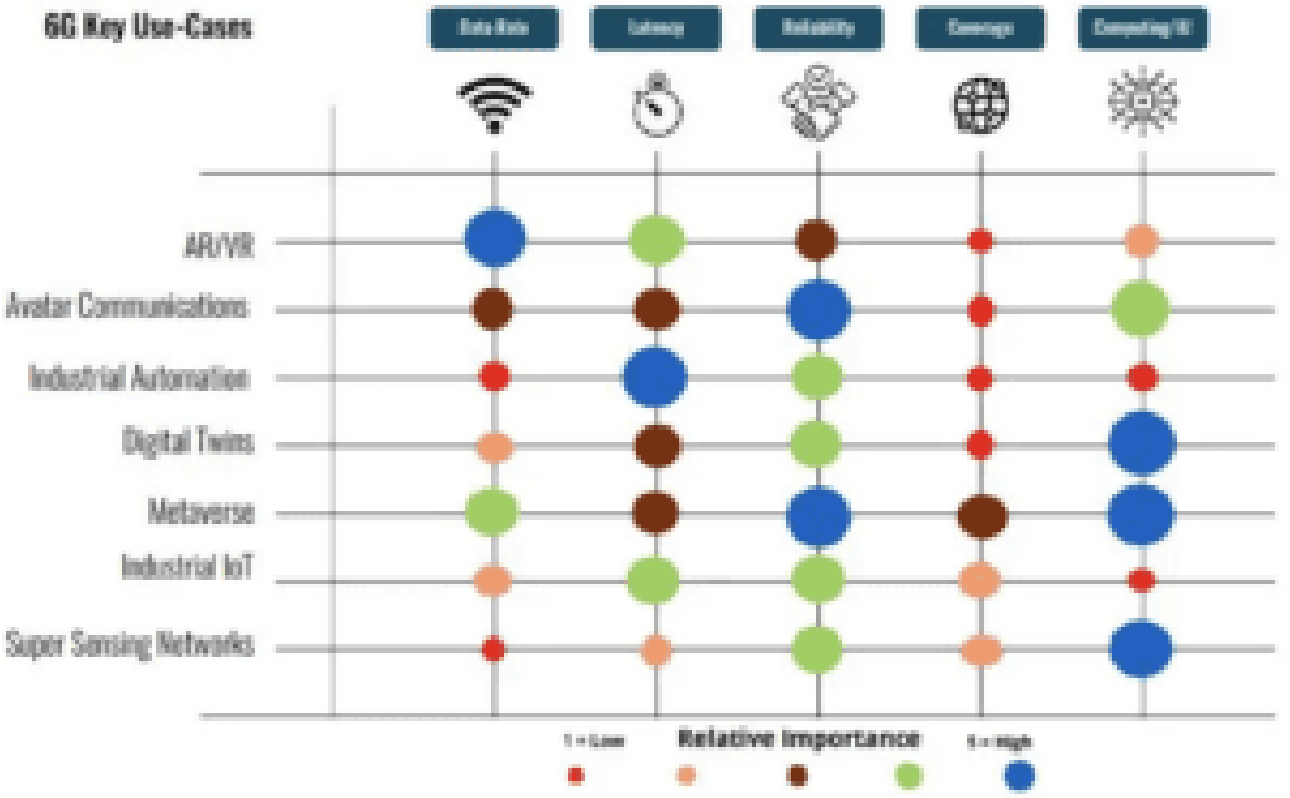
I already addressed the crucial technologies that are needed in the operation of the Industrial Metaverse. Let me now take a more system wide perspective, considering a few basic aspects that enable the creation and operation of an Industrial Metaverse.

Connectivity structure

Let me start with the connectivity structure of the Metaverse.

Connectivity is at the core of our life, well before we had connectivity infrastructures. Our ancestors gathered around a fire camp and used voice and visual signs to "connect one another". Then came the exploitation of rivers and then roads and much later written text and then books. Current telecommunications is just an instant in the journey of humanity although today it would be impossible to live without it.

Today's telecommunication infrastructures are amazing, pretty close all people and all business are connected in today's world. Wireless communication changed the shape of the world, making communication pervasive and most important affordable (almost) everywhere. We have 5G with amazing bandwidth, speed and low latency, yet for most of our needs 4G is plenty. That includes industry with massive use of WiFi as well. By the end of this decade 5G will be what today is 4G in terms of penetration and it will be the new metric to gauge basic communication performance. At that time 6G will become available and although most people are content with 4G researchers are studying what could be achieved with 6G and the emerging consensus goes in the direction of becoming the connectivity structure for the Metaverse.



It is interesting to notice how all use cases being developed for 6G are directly addressing the Metaverse or are instrumental to Metaverse operation (and access). In this graphic an example of this strong association between 6G and the Metaverse. Image credit: ABI Research

Take a look at the graphic, taken from a nice article on "How the 6G would work for (and in) the Metaverse". It lists 7 areas, one being the Metaverse, but if you look at the other 6 it is easy to see that each of them is related to, a component of I would say, the Metaverse. The matrix connects each of these areas to a connectivity characteristic sustained by 6G, with the size of the connecting dot mirroring its importance:

- Augmented/Virtual Reality (and I would add Mixed Reality) is what enables the access, the living in the metaverse. Considering the kind of visual details that have to be captured to create a seamless feeling of reality it is obvious the importance of very big bandwidth, as objects have to be displayed with twice 4k resolution (4k+4k to provide depth of field, 3D perception) have to be displayed. Depending on the architecture used for visualisation even higher resolution might be required (to allow for closer inspection, as an example) although gimmicks can be used to deliver the same experience at lower resolution. Almost as important is the low latency to avoid artefacts showing up when turning your gaze in the metaverse landscape.
- Avatar communications. Basically every entity in the metaverse will have a life of its own with each potentially needing to interact with any other. This calls for reliable communication as well as some kind of intelligence to understand the context and adapt the interaction accordingly. Notice how in the matrix Artificial Intelligence and computation have been aggregated into a single class. Also, notice that one of the characteristics of the 6G connectivity will be its bottom

up creation and interworking, assuming localised and massively distributed intelligence.

- Industrial automation (read robots communication and soft robots interaction) requires in many situation a very low latency and, of course, high reliability.
- Digital Twins, as already noticed will have embedded intelligence and will act autonomously. Hence the importance of computing capabilities and artificial intelligence, both as part of the context and embedded. Digital Twins may become network nodes in certain situation and to carry out specific activities. 6G will both make use of digital twins to provide its services and be a fabric used by executable digital twins.
- Industrial IoT. It represents both the data input stream generation and, in most cases, a decentralised distributed intelligence. Low latency and reliability are crucial factors, even though in most cases it will be possible to create architecture and data processing that can be resilient to some degree of connectivity disruptions and to slightly unreliable data.
- Super sensing networks. These are basically industrial IoT on steroids with local intelligence. As an example, they can autonomously decide what to sense and the kind of sensing to perform leveraging on local intelligence and providing meaningful information, as opposed to raw data. For this the main demand is on computation and AI.
- Metaverse. Here the focus is on reliability, computation capability/Ai and on bandwidth, not surprisingly. However. notice that all the other areas are also part of the metaverse and each has its own demand on connectivity.

I would add that with the 6G vision (we are basically at this stage today) the metaverse can become itself the connectivity fabric, with several of its components doubling up as network nodes and connectivity providers.

Computational Power

Industry has embedded processing powers in all its area and a factory today has -most likely- more processing power that the most powerful supercomputer, if we add up all the number crunching chips disseminated on the shop-floor, not to mention the one contained in many products. The list in the figure shows the processing power, measured in instruction per second -a very poor metrics!- of several devices.

A curious comparison of the processing power, measured in number of operation per second of several devices. Our brains still tops the list, with the Tesla microchip supporting full self-driving ranking second. Notice that: the representation uses a logarithmic scale, the Tesla has 1/14 of the processing power (in terms of operation per second) of a human brain; measuring the processing power by the number of operation per second is grossly misleading (but it may be fun!). In spite of the much higher number of operation per second a human brain would not be able to do the processing of the Tesla microchip and conversely, a Tesla microchip won't be able to do some analyses that a human bran does. Image credit: CleanTechnica

Independently of the meaningfulness of those number, one thing is clear: over time the processing power available skyrocket, hence processing should not be seen as a barrier for the industrial metaverse.

What should be considered is that, indeed, the metaverse requires plenty of processing power, possibly two orders of magnitude with respect to what a factory has today. At the same time, an increase of two orders of magnitude in processing power are easily met within 6 to 7 years, so by the end of this decade factories can expect to have the processing power it takes to fuel a comprehensive metaverse.

It should also be noticed that this processing power comes, and will come, in different forms:

• Sensors: IoT will keep growing their processing power, both as a single IoT and as clusters (see the STM32 familyto support AI at the level of IoT)
• AR/VR goggles: VR devices have increased processing power, even though they have to reach a compromise with battery use. The announced Meta Quest 3 has some 2 trillion Flops, equivalent to the processing power of the Mars Rover. We can expect much more processing power by the end of the decade and many workers on the shop-floor will have one of those. Allso notice that VR is processing power hungry and it won't rely on the user device only for quite some time. Some processing, and pre-processing will need to be done elsewhere.

- Equipment: robots and most equipment used on the shop-floor will have plenty of embedded processing power. The orchestration of activities, through interaction in the metaverse, will make (part of) this processing power available to operate the metaverse. Remember that I mentioned in the beginning of this

discussion on the metaverse that on of its characteristics is the decentralisation and that its operation fully exploits decentralised capability. This is so also for the processing part.

- Cloud support: both local and network cloud will be part of the industry processing power, with local cloud taking care of those activities requiring very low latency.

The metaverse, both the consumer and the industrial metaverse, is most likely to be "fluid", not rigidly designed. It will be composed by parts that were produced by different players and the power of the metaverse derives from the interactions taking place. It is the sum of all these interactions that gives the metaverse its identity. Think about an anthill: its behaviour and characteristics emerge from the sum of the behaviours of individual ants and there is basically no anthill director to orchestrate their behaviour. There is a framework (chemical communication mostly) that results in an ordered operation of the anthill.

A metaverse will have some of these characteristics of small worlds emerging intelligence. The challenge. of course, is to be able to design such a framework. The MPAI standardisation activity has basically this goal.

Digital Twins fidelity

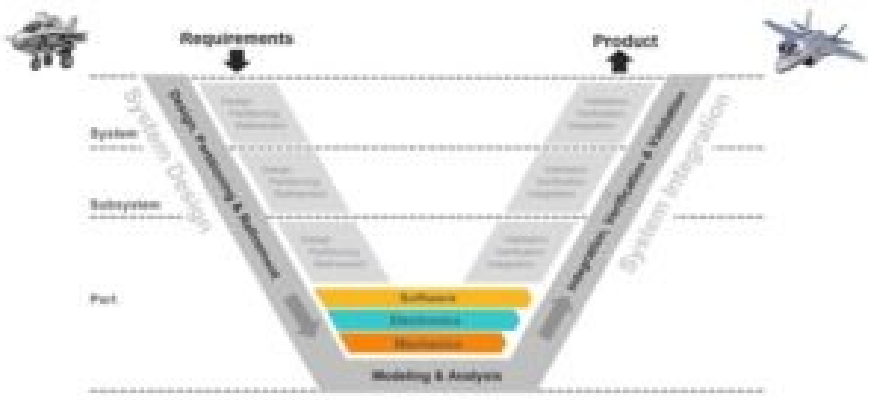


Diagram representing the normal design to manufacturing process, in this case applied to the design and manufacturing of a fighter plane. Digital Twins are used from the very start and get enriched more and more with details as the design progresses, then further more as the plane is manufactured. Image credit: Frank Schirrmeister

A Digital Twin is not exactly like the real thing: you cannot wash your laundry with the Digital Twin of the washing machine!

Yet, you can do plenty of things with the digital twin of an object, even something that you cannot, or you wouldn't do with the actual object.

To understand this, and the implication, let's look at how a digital twin is created. As shown in the figure, in manufacturing you usually start creating your digital twin from the very beginning of the design phase. You may want to start with a Digital Twin broadly representing your target system. That way you start identifying the various functionality *AND* the set of interactions your real system will have with the ambient it will be operating in.

Ideally, you already have a data space describing the ambient and possibly some digital twins that operate in that ambient (mirroring the objects operating in that ambient). You can start doing some emulation of your (future) system in that ambient

and see how it works, or -better- how it should work. This should lead to identify subsystems, and each of them will -most likely- generate its own digital twin. It is also most likely that the generation of the digital twin of a subsystem will be done by a different person/team/company, having the needed competences.

These subsystem digital twins can be checked against the first system-wide digital twin to ensure that -all together- they deliver the expected functionality and behaviour. This creation of subsystems, and related digital twin seldom keep the system wide digital twin unchanged. As you progress in the design, you are adding details, and facing constraints. These, in turn, often lead to (hopefully) small changes in the overall system design.

Either way, your original system-wide digital twin becomes enriched with more details, becoming closer to the final manufactured product.

This process can go on and on. In the figure it has been simplified in three layers, system, subsystems and parts. As you (the company) progress in the specification your digital twin(s) become more and more detailed, approaching more and more the product. Once the design/specification phase is completed (this includes extensive modelling, simulation and analyses) for all parts to be manufactured (software, electronics and mechanics in this example) you can move to the manufacturing phase. This proceeds from the manufacturing of the individual components to their assemblage into subsystems and finally into the complete system. Along this process, the digital twins are used to support verification, validation and integration, by connecting to the product being manufactured. In the metaverse this connection happens through other digital twins, like the ones representing the assembly line and the robots on the assembly line. It is only after the product has been manufactured and released that its digital twin instance is connected to the physical product via IoT embedded in the product.

As manufacturing takes place both the digital twins and their instances, one for each product manufactured, are enriched with further details (including the ones related to the manufacturing process itself, like who performed a given assemblage - both robots and people, hiccups in the process ...). Once the product is released its digital twin is a faithful digital copy. It should also be noticed that in some cases the digital twin (instance) is charged with delivering some functionality. It is a design / architectural decision to have the digital twin (instance) actually delivering the functionality or to keep the digital twin (instance) as a copy of the physical object and use an associated digital twin to deliver the additional functionality.

The question is: how faithful is the digital twin, or, how faithful should it be?

This is a crucial point in the construction of the industrial metaverse. Digital twins are the "characters" operating in the metaverse and they have to be "credible", i.e. they should represent the object behaviour in the physical space.

Actually, the object behaviour perceived may differ, depending on who is observing it. A casual observer will see just the outside of the object, and its interactions with the environment. A user can experience what it takes to use the object, an engineer

can look "inside" the objects to see its cogs and wheels workings. Each of these "observers" will need a different level of "fidelity".

These different levels of fidelity will become visible in different frames, so that each observer (that includes also other digital twins roaming the metaverse) will get his/its own perception of the object (and each of these perceptions should be credible!).

From the industrial metaverse viewpoint there should be a clear definition of what belongs to a frame and what not.

Interoperability

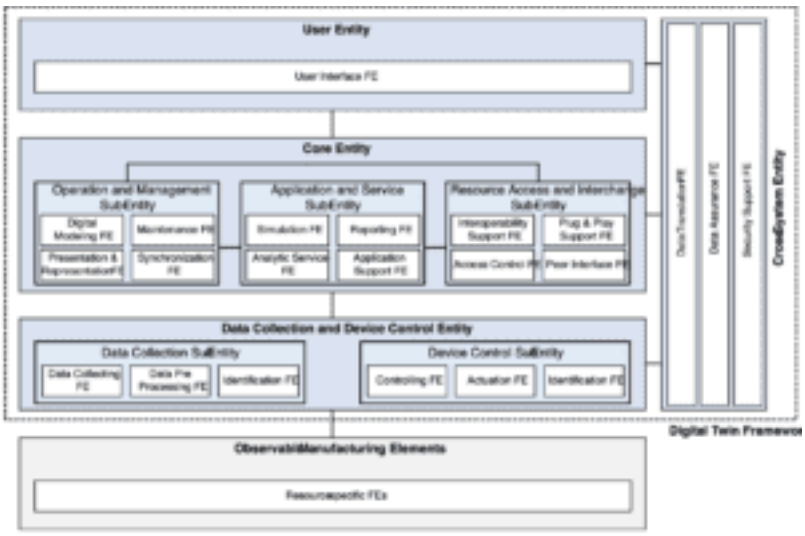
Diagram showing the proposed architecture for Metaverse instances interoperability. Image credit: MPAI

I have already pointed out that today we have many proto-metaverses and that my feeling, shared by most observers, is that we will have many metaverses in the future. Hence, the effort shall be not to try to converge on a single metaverse, rather to make metaverses interoperable. Actually, there are two aspects of interoperability:

1. interoperability of entities within a single metaverse
2. interoperability across several metaverses

Let's look at each one.

1. *Interoperability within a metaverse*



The four layers defined by ISO for the creation and operation of Digital Twin in manufacturing, Image credit: ISO[/caption]

Entities "living" in the metaverse may have been created by different parties, using different tools. Yet, they will need to interoperate. Most crucial, in an industrial metaverse, is to ensure the interoperability of digital twins.
In the industry application of Digital Twin there is the ISO 23247 standard, Digital Twin framework for Manufacturing. This standard defines four layers to create and operate digital twins in manufacturing, The lowest layer is actually the physical manufacturing floor containing the entities that need to be described/represented by digital twins. As such you can say that it is not part of the standard. The layer above represents the communication based on data (including the harvesting of data through IoTs) and the control of the entity, The layer above describes the functionality of the entity, i.e. it models its behaviour. The upper layer is the presentation layer modelling the representation of the entity to the end user. This layer is particularly important in the industrial metaverse since this is what the human user will see and interact with in a life-like manner. Notice that this layer can support different representations, fitting different frames, so that, as an example, a lay user will see a different representation of an entity form the one seen by an engineer in charge of monitoring that same entity.The coherence of data (meaning, structure) is clearly essential. In this area Gaia-X is working defining data spaces in vertical sectors, like automotive.

2. *Interoperability across metaverses*

As mentioned we can foresee the co-existence of many metaverses, each one generated by a (or a cluster) of player(s). Over time we can also expect that a few of these metaverses would merge to create a broader metaverse. In order for this to be feasible interoperability across them shall be ensured. This is where the MPAI initiative comes in. As it is shown in the diagram, the MPAI specifies a number of interfaces to ensure interoperability. It also specifies a standardised data format that, if adopted within a metaverse can

ensure direct interoperability with other metaverses adopting the same standard.

Interoperability is likely to be fostered by the adoption of open platforms. Current industrial platforms supporting Digital Twins, like Mindsphere, are most likely to evolve to support the industrial metaverse and as such they will also provide interoperability to all metaverses supported by them.

These platforms ensure interoperability across the value chain, mostly between suppliers and the manufacture and between the manufacture and the delivery chain. The adoption of the Industry 4.0 paradigm will extend this to the user layer.

Beneficiaries of this evolution are the SMEs - Small Medium Enterprises- that may not have the knowledge and capital asset to enforce their own metaverse but that can piggyback on existing metaverse, reaping the benefits.

The next economy

A crucial aspect for the long term success of a metaverse is its economic viability. As in the physical space trust is what keeps users coming back. Image credit: Appinventive

As it happened, and happens, with the Digital Transformation -DX-, industry adopting the metaverse as their new environment have to re-consider their business models and evaluate the economic implication.

The digital space and the metaverse, includes a digital space, has potentially no boundaries, everything is co-located, and just one click away (by the way, being one click away is not a given, is part of the designed architecture: when I wander on Amazon I am just a click away from buying anything, when I am on an Italian Government website I am in a nightmare of clicks after clicks trying to reach my destination!).

This enhanced simplification is great for industry because it increases efficiency and cuts cost. However, what is simplified for one is also simplified for many others that can become more competitive. Additionally, the barriers to entry crumble (or get significantly reduced) thus further increasing competition.

There is a BUT: to really exploit the enhanced efficiency and lower cost the industry needs to re-think its processes, basically redesigning them from scratch. Failing this the industry will add to existing cost the ones deriving from operating in the digital space (if you shift your documents to a digital format but still required a physical signature so that your people need to print the document and archive the physical version you have just added cost and wasted more time!).

The metaverse can be seen as a further step of the digital transformation, may be a DX 2.0. If you are creating a factory that is partly in the digital space and you take all the burden of creating visual digital twins, then you must enable visual interaction to exploit them.

If you operate in a metaverse, part of this operation has to include/support economic transactions, all (most) in digital form.

In a metaverse you are creating, and dealing, with value. Hence, you must protect your assets as well as you protect asset in the physical space. Actually, you should be even more careful since now your assets are on the world square, everyone can be within reach of them. The more valuable they are, the more likely to attract unwanted attention.

Also notice that whenever you are stepping into the economic side of a business you are also entering the regulatory space. Indeed, regulation needs to be in place to sustain fair thrift and economic exchange.

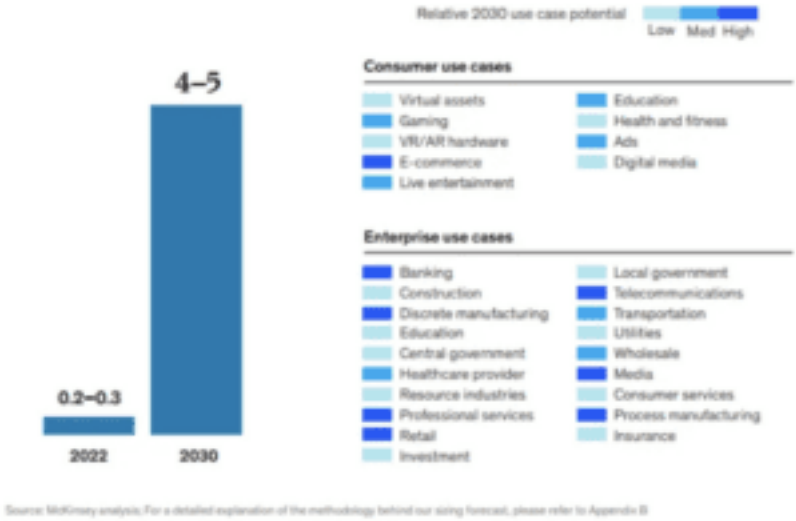
New financing tools will be needed to support the digital world. This point is stressed in the MIT - Siemens report, noting that this will require cooperation among financial institutions, machine builders, end customers and technology / service partners across the whole ecosystem.

Conclusions

The industrial metaverse is here to stay

The Metaverse, as any "new" things, suffers from hype and it is not unexpected to hear many raising warning flags on what they feel can be a bubble that will be fading away pretty soon. It won't be the first, nor the last.

Yet, if you step back and take in the bigger picture you'll notice that the megatrend towards digitalisation and the related virtualisation is extending across many sectors, in some places it is moving quickly, in others is slower but the direction is clear.



Forecast of the increasing value of the metaverse expected to reach 4-5 trillion $ by 2030, with indication of adoption in various areas. Image credit: McKinsey

Governments all over the world have clearly set the goal of digitalising the public administration, promoting digitalisation in the private industry. Sustainability and concern on lack of resources are also pushing towards digitalisation. These are powerful forces towards the progressive digitalisation of a significant part of business and of our everyday life.

Having said that the creation of a digital space is an unstoppable trend we also have to acknowledge that our life is lived in a physical space. Keeping these two spaces separated from one another makes little sense, Hence, the metaverse is just a consequence of these general (mega)trends.

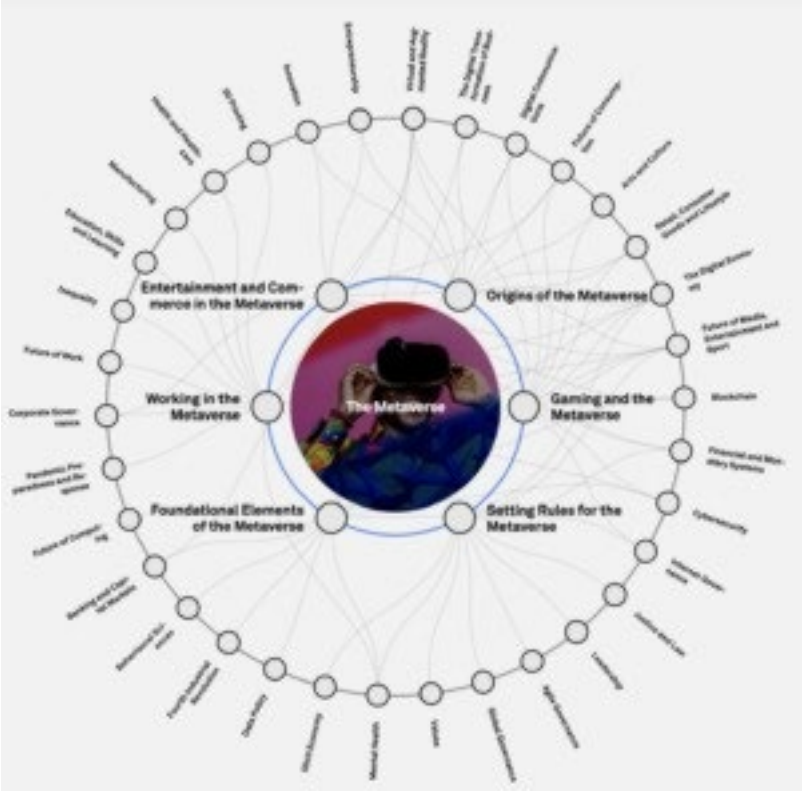
The level that the metaverse will (can) reach remains an open question as well as the timing. However, the question is no longer if but:

- what will the metaverse be by the end of this decade? Will there be only one metaverse providing access to many (niche based) metaverses or there will be a constellation of many independent, not interoperable metaverses?
- how will a metaverse look like, a copy of the physical space recreated in the digital space accompanying the physical space or a physical space expanded by a digital space that is completely different from a digital space?
- what will be the evolution steps?

It is most likely that the evolution will be driven by the availability of access gateways, goggles and other interfaces to connect our senses to the digital space. Personally, I see a very fast evolution of some metaverse components, like AI, digital twin, image rendering, ... but a much much slower evolution of human-metaverse interfaces. A true seamless space where digital and physical are perceived as a single space is unlikely to happen in this decade. At least, this is my bet.

On the other hand, the benefit derived from the adoption of proto-metaverses that will become more and more performant over time will stimulate more and more companies to adopt it. At the same time this growing adoption will stimulate investment and fall out in the consumer market.

Don't lock yourself in



The metaverse and its many relationships. Image credit: WEF

How much should a company (industry) open up its metaverse? Clearly it is a space containing valuable assets (both digital and physical) and the relationships and interactions among the various components are themselves a value. Hence, it is no surprise that in the same way as a company protects the access to its sites, it would design a closed metaverse to keep out those that are not part of the "club".

At the same time, as it is noted in the MIT Siemens Report, when you lock other companies out you are also locking yourself in. And here lies the problem. The digital space kills distances but if you lock yourself in you are becoming an island, losing all the benefit deriving from being part of the whole world.

A compromise, following the evaluation of risk and benefit, has to be found. Opening does not mean to lose control on who can be part of the metaverse and what role it can play. On the contrary. Open means to define an open architecture supporting different roles and fostering interoperability.

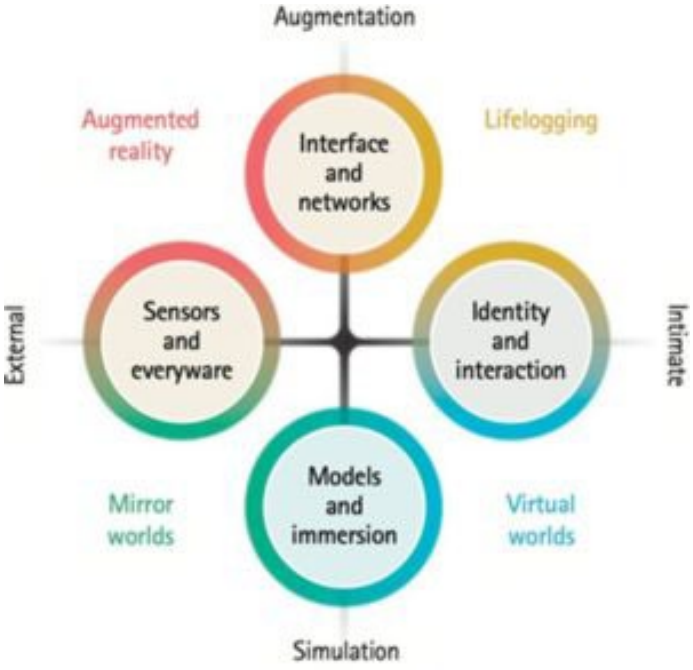
There are a few organisations pursuing this goal, like the already mentioned MPAI, the World Economic Forum (see the graphic and explore) and the Metaverse Standard Forum.

Adopting these open standards is essential to make sure that the company can share -what they want to share- with other parties, like a new supplier or a customer.

The industrial support platforms, like Mindsphere, are adopting these standards, as an example for Digital Twins.

The definition of interoperable data spaces (GAIA-X) is also crucial.

What is it that you really want? that you really need?



people and in different application spaces. This diagram shows a positioning space, from simulating something that is not there to augmenting something that exists, from being a shared experience to an intimate one. This goes for a consumer as well as for an industrial metaverse. Image credit: Is Metaverse in education a blessing or a curse: a combined content and bibliometric analysis. Ahmed Tlili, et al. Beijing Normal University

I take for granted that an industry considering to adopt the industrial metaverse has already executed its digital transformation or has decided to execute it and make the shift together with the adoption of the industrial metaverse.

Having said that the question is: what is the metaverse I should be aiming at, what purpose would it serve?

As I pointed out there can be many interpretation of an industrial metaverse and these are mostly related to what activities are planned to take place in it and therefore who is going to use (and operate in) it.

As pointed out in a previous post, we can have several layers of an industrial metaverse, each one tied up to a specific phase in the life cycle, design, supply logistics, manufacturing (shop-floor), customer interaction, customer use. Not necessarily a company mzy want to cover all of them. Actually, it can make much more sense to start with one, see how it works, learn from experience and then make a further step extending the metaverse to include another layer.

So, where should a company start from? As usual, the advice is to harvest the low hanging fruit first, How do you define "low"? Well, the area where the investment required is lowest (in tools, equipment, skills, process re-engineering) OR/AND

where the benefits are higher. Time of execution may also be an important factor, lie possibility to monitor the benefits.

This leads to these options:

- manufacturing layer: a shift to the metaverse may improve the cooperation among blue/white collars and robots, can improve flexibility in the organisation of the shop-floor. On the minus side it can be costly in term of re-skilling, re.engineering of processes, workforce organisation and need of new equipment.
- design layer: this is possibly the easiest one to implement the shift, assuming design is already happening in the digital space since the workforce involved is already skilled, equipment to interface with the digital space is already in use and the amount of process re-engineering is limited, However, the benefits that can be expected are more limited than the ones achievable through the shift of the manufacturing layer to the metaverse.
- customer layer: using the metaverse to connect and interact with customers is not particularly difficult, nor costly since a good portion of the investment required is on the customers shoulders. The benefit that can be achieved can be significant (24/7 customer support, creation of effective self-helping customers community, ease of communications) However, and this is why I listed this as last, it is a big question mark to predict its success since it depends on the customers adoption. The company can work hard to create an enticing metaverse but there's no guarantee on customers acceptance.

These three layers have in common the (almost) full control by the company. The other layers (like the supply chain, ..) involve third parties so they may be more difficult to orchestrate.

Sometimes the shift may be forced from the external, such as your company is a provider to a major company that is enforcing operation through the metaverse. In this situation you have to shift your activities towards that company to their metaverse and, de facto, enter into a metaverse operation. However, this can be seen as an opportunity to re-think your operation in more general terms.

In general, the advice is to set clear, measurable, objectives to be achieved by shifting to the metaverse and track progress. Not very much different from any major, uncertain, goal leading a restructuring of a company.

Tricky issues across empowerment and control

The metaverse is all about knowledge access and exchange. Knowledge is distributed, i.e. owned by different parties: human, organisation, machine. The HR role becomes the one to ensure knowledge accessibility and leverage.

Top skills needed, and sought after by industry, for resources to fit into today's business world. Notice the number of soft skills required. Operating in the metaverse requires them all and, at the same time, can reinforce them all. Image credit: LinkedIn Report

The industrial metaverse is a working space, a new working space. As for any working space resources need to be trained. Robots need to be able to operate via their digital twins, interactions with one another need to take place via their respective digital twins and interactions may involve other digital entities. The adoption of artificial intelligence and the possibility to accrue experience and modify the behaviour makes adaptation to the metaverse both easier and trickier. Whilst the former is obvious the latter may need some explanation. The overall behaviour of the system in the metaverse should be predictable, i.e. according to design. However, as the digital entities learn, they can change their behaviour leading to unplanned, and unexpected, behaviour. Here there is a tradeoff between the need to ensure a "proper" behaviour and the value that derives from flexibility (creativity?).

Clearly, the digital entity learns and adapts evaluating the results of its interactions (activity both in the digital and in the physical space that is mirrored back in the digital space). This evaluation is made against a goal along with a set of parameters (speed, use of resources). However, the goal is not everything. It is also important the way that goal is reached. This requires the definition of a framework of operation that provides the boundary of acceptable behaviour to all the digital entities.

This goes for human resources as well. As in any operation (working) environment, the human resources should have the skill that both allows them to perform the needed activities and that makes feel them at ease with those activities. This, as for any other endeavour, requires training.

However, in the metaverse (depending on the type of metaverse and the type of operations) the situation can become way more complex since there can be a mediating entity that is actually operating in the metaverse as a proxy: the personal digital twin of the person. How can it be ensured that the digital twin is really and faithfully representing the person? What level of independence can a personal digital twin have?

Of course one can decide, and this can be the first step, that the personal digital twin is only a digital interface to operate in the digital space. In this situation the physical

person has full control. However, this also limits the potential of operation in a metaverse, where digital proxies, like personal digital twins can take over without the direct control of their physical twin.

If the personal digital twin acquires autonomy (and there can be many different levels of autonomy, each more performant but at the same time more problematic) two main issues arise:

1. how to ensure that the personal digital twin would behave as the physical twin would (sharing the same ethical, societal, and cultural framework)
2. how to recover synchronicity between the personal autonomous digital twin and its physical counterpart.

The first aspect is not trivial. One can, of course, define the operational space, as already mentioned for digital twins of machines, but it may be impossible to cover all potential situations and interactions. In the end we, human being, exercise our own "wisdom" to tackle all unexpected situations. Mirroring this "wisdom" is no trivial matter.

The second aspect is even more difficult. As our personal digital twin becomes autonomous it is also gaining experience and, through embedded AI, can transform this experience into knowledge. Actually, the use of GAN -Generative Adversarial Networks- can lead to an exponential growth of (simulated) experience and thus growth of knowledge and catching up soon becomes impossible.

By having our personal digital twin flanking us we can tap onto that knowledge, augmenting ours, as need arises. This, in turns, open up new scenarios. This augmentation occurs only when we are in touch (seamlessly) with our personal digital twin but that would happen only when we are in touch with the industrial metaverse hosting it, Additionally, the knowledge is being shared, implicitly, through interactions, within the metaverse and can easily be captured by the metaverse itself, hence becoming a company owned knowledge.

Technology advanced possibilities, particularly those deriving from AI, open up a can of worm.

Creating internal support - Personal Digital Twins

As any profound change, the shift towards the metaverse requires the consensus of all those involved. Ideally you would like to have more than consensus: active participation, contribution, willingness to solve obstacles popping up on the way.

As previously mentioned, empowering people can transform a passive workforce into a co-designing team. The challenges are very similar to those faced in the digital transformation and, if such trail has already been walked, or is being walked, it is most likely that differences in acceptance an commitment have manifested among the workforce. It makes sense to leverage on those who have shown their

commitment and, at the same time, work on those who haven't, trying to understand why.

The HR department played a crucial role in generating internal support preparing people to address the new way of working and ensuring coherence throughout the activities. You cannot "empower" a person and then evaluate that person on working time. Results are what matters. The digital space offers much more latitude in ways of becoming involved, geographical as well as time barriers may lose importance.

It does not make a lot of sense to tell your people that the company is moving to operate in the metaverse and then ask them to be physically present on company's premises…

In my experience the coherence is an essential factor in creating an internal support. People should feel the change as a win-win situation, they should perceive both the advantages for the company (lower cost, increased efficiency) - notice that this is essential, any transition requires an effort and it should be clear that such effort is worth the result!- and for the team, and the single individual.

As an example:

- Operating in the metaverse will let you experiment with ideas, be "concretely" more creative, since the cost of resources in the metaverse is minimised;

- Having a Personal Digital Twin of yourself will provide you with a proxy that can take care of repetitive chores. If the Personal Digital Twin is more advanced (autonomous) you can task it with harvesting data/information/knowledge to help you out in a variety of situation;

- The Personal Digital Twin is … "personal", hence you have full control of it and full ownership. This means that it is up to you to decide when and how to use it. However, you are responsible for your Digital Twin, as you are responsible of the use of any tools provided by the company. This means that your Personal Digital Twin is subject to the rules set by the company (these are usually "enforced" by the Metaverse).

- If you leave the company your Personal Digital Twin is no longer inhabiting the company metaverse. However, the knowledge/expertise that has been accrued in the metaverse by the company (e.g. by the Digital Twins of the robots that have been interacted with you/your Personal Digital Twin) will remain in the company.

- As a company may provide tools for helping in the creation and operation of their workforce Personal Digital Twins, the company may also hand over to you your Personal Digital Twin once you live the company so that you can still use it (in a different metaverse or as a personal assistant. Standardisation can make this feasible. If that is the case this become a benefit that should be emphasised.

There are plenty of aspects that can become a benefit to any individual in the workforce when operating in the metaverse. It is important for the company to make people aware of them to stimulate inclusion and commitment.

Notice how the creation of Personal Digital Twins is both a tool and a lever for the HR department. The Digital Transformation and even more so the shift to the industrial metaverse change the approach to people management since it becomes possible to manage beyond the activities, i.e. manage the knowledge accrual and exchange (among people and among people and machine).

These aspects have surfaced in the definition of knowledge digital twins and have become part of the Knowledge as a Service platform, now available to IEEE members. The development has involved HRCoffee, an innovative company that focus on the evolution of HR and aims at supporting the new operational framework through innovative tools. I spoke recently with the CEO and CTO of HRCoffee and they told me that within the next 3 years they expect to see significant adoption of Personal Digital Twins in companies and they see the HR taking responsibility for managing and leveraging them. In other words, the shift is from managing physical resources to managing knowledge, as shown in the graphic at the beginning of this section.

Creating external support

The Industrial Metaverse may start as a local space, fully owned, used and inhabited by a company (like for the design of a product). However, its natural evolution is towards becoming a shared space, open to other parties that are part of the same value chain or/and ecosystem (see “Don’t lock yourself in”).

The previous discussion on the natural shift towards knowledge management connects directly to the need of a company to create an external support. Knowledge has become so vast that it is impossible to pursue the ownership of all knowledge and even the pursuit of the needed knowledge may not be economically feasible. In

the same way that companies have outsourced the production of components, it makes sense to outsource knowledge.

The Metaverse has many facets and involves many components. In turns several players are offering solutions. The whole landscape needs to be considered by a company considering the shift. Image credit: Metaverse for future engineering, Xiangyu Wang et al.

Shipping components from one part of the world to the assembly line “just in time” has become a competitive tool for companies. Likewise, getting the needed knowledge when and where it is needed is becoming a competitive edge. The industrial metaverse is enabling just this. There are no boundaries, nor friction, to knowledge availability and there are tools, cognitive digital twins, to make this knowledge executable (usable).

This requires the opening of the industrial metaverse to the participation of the companies and individuals (like consultant, temporary workers, organisations -like IEEE- focussing in specific knowledge domain). It is through the interactions and knowledge exchange among all these parties that innovation will be generated.

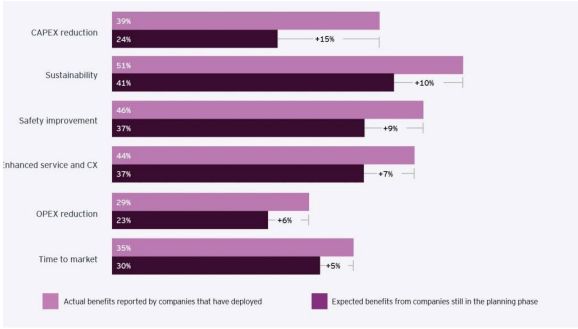
In the MIT Siemens report the point is made by illustrating how Konnect Volkswagen Group in Tel Aviv uses the metaverse to bridge the knowledge generated by Israeli start ups with the German parent company. They are using mixed-reality technology to support design, manufacturing and training in a virtual environment.

Nokia head of trend and innovation, Leslie Shannon, is pursuing multi-player partnership enabled by the metaverse to increase business agility.

All this requires standards and a common platform that “enforces” homogeneity in data (meaning) and interactions. Siemens Mindsphere has been flanked by Xcelerator digital business platform to help a variety of players in the value chain to access and use the industrial metaverse. The platform connects manufacturers, service providers and customers using open interfaces and a scalable environment.

The overall message brought forward by the MIT Siemens study is that the industrial metaverse is a growing reality. It does not have the hype of the consumer metaverse but it is a consequence of the digital transformation and as such it will be adopted more and more.

Good vibes from current industrial metaverse



Actual benefits reported by companies who are (partly) operating in the metaverse versus expected benefits by those who are in the process of shifting operation to the industrial metaverse. Notice how reality exceeds expectations. Image credit: Ernst & Young, Nokia

It is appropriate to conclude this lengthy discussion on the Industrial Metaverse with a look at what are the results obtained by companies that made the shift (in most cases it is a partial shift, so the benefits are evaluated against the part that has shifted to the metaverse).

These considerations are based on the study carried out by Ernst&Young and Nokia published in a June 2023 report.They polled several industries that have moved part of their activities to the metaverse and others that are planning the shift. The graphic shows the outcome and it is interesting to note that in all aspects the actual experience has exceeded the expectation. It is also interesting to see the benefits that can be derived from the shift:

- Capex reduction: operating in the metaverse (to be expected since this is a fall-out of the Digital Transformation) leads to a reduction in Capex experienced by 39% of the companies (and expected by 24%). If these percentages seem on the lower side consider that this is likely to be a starting point. There are investment to be considered that over time will decrease (both because you need less and because technology cost decreases) and, most important, there are lessons to be learnt to get rid of the previous “modus operandi”, in other terms you need to re-engineer your processes to decrease the cost.
- Sustainability is a direct consequence of turning to bits as raw material, decreasing the need for physical resources. This aspect, however, needs to be taken with a grain of salt. What can be perceived as an increase in sustainability by the company may actually place a burden on the whole system (using bit does not pollute the company space but the increased electrical power required to handle those bits, both in the company and in the cloud may lead to pollution elsewhere depending on the way electrical power is generated). Here again the actual experience exceeds expectation.
- Safety improvement would also seem a given, Smashing on a bit, even a stream of bits, doesn’t hurt you. However, here again the whole scenario has to be taken into account. The metaverse includes the physical space and you have to be careful that actions generated through the digital space are not harmful in the physical space. Let’s say that statistics show that many accidents are resulting from human mistakes, due to fatigue and distraction. Avatars and Digital Twins should not be affected by that so if the system has been designed with focus on safety the overall safety should increase.
- Enhanced service and Customer relations are benefitting from the always on of the metaverse and the possibility to instantiate interactions and personalize them.

Metaverse scale up seamlessly (mostly…) so that it can always to responsive, here and now, to customer needs and can actually anticipate them by interacting with the digital copy of the customer through the use of a product/service. The digitalized customer care has to thread a thin line between customer support and intrusive monitoring. This is, by far, a subjective evaluation and there should be mechanism to let the customer decide where the dividing line should be placed.

- OPEX reduction is the lowest experienced benefit, less than a third of companies have experienced a reduction. However, I suspect that over time as processes get re-engineered based on experience, this area will become a significant one.
- Time to market is improved in 35% of companies. I guess this may depend on the type of business you are in. In general, it is easier to create digital prototypes and use them for simulation. This should lead to a quicker design phase. Also, this provides more flexibility in the manufacturing process that can be executed up to a certain stage in the digital space, hence changed rapidly if need arises.

Like for the Digital Transformation (I already mentioned that to me the industrial metaverse can be seen as a DX 2.0) the Industrial Metaverse will take time to be executed by a company and to spread to (contaminate) other companies but the process has started and will move on.

Further readings

1. Digital Reality Initiative White Papers.
2. Digital Twin Market: Global Opportunity Analysis and Industry Forecast, 2021–2030. Pankaj, M. Neha, and V. Vitika, Allied Market Research, July 2022.
3. Emerging Technologies: Revenue Opportunity Projection of Digital Twins, Alfonso Velosa and Peter Middleton, Gartner, February 16, 2022.
4. Emerging Tech: Venture Capital Growth Insights for Digital Twins, Alfonso Velosa, Gartner, September 21, 2022.
5. What Is the Industrial Metaverse? Capgemini, February 6, 2023. Jacques Bacry
6. Accelerating sustainability with virtual twins, Simon Bentley and Tony Murdzhev ,Accenture, January 26, 2021.
7. The Metaverse at work, EY and Nokia. https://www.nokia.com/metaverse/industrial-metaverse/the-metaverse-at-work-research/

Webinar recordings:

1. Future Technologies and Metaverse, Roberto Saracco, Latin American Forum, May 2023. https://www.youtube.com/watch?v=RD39IT6QQs0
2. Industrial Metaverse, Roberto Saracco, FDC Metaverse Initiative, July 2023
3. Industrial Metaverse Perspectives, Roberto Saracco, EIT Manufacturing, July 2023