The Fourth Industrial Revolution in the Context of Past Industrial Revolutions: A Systematic Analysis

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0. ABSTRACT

This work aims to contribute to the research question: How can understanding the past three Industrial Revolutions help industry prepare for the 4th Industrial Revolution, maximizing its upside and minimizing its downside?

This question was addressed through a systematic analysis of the past industrial revolutions, from which a framework was emerged and was developed: the framework for industrial revolutions (FIR). This presents technology, energy and institutions as key factors and integrates them. FIR was applied to past industrial revolutions. The findings were used to address the 4th IR and were also tested against a specific complex problem: the stagnation of economic growth in Western economies after the 1970s.

FIR has identified the introduction of energy sources, and their qualities, such as energy density and enabled second law efficiency, as important factors to explain the Pre-Industrial Era and the first two IRs. On the other hand, in the 3rd IR there is no introduction of a new energy source, or of any new process that changed substantially energy efficiency. Also, apparently, in the 3rd IR, the technology introduced had not such a visible effect, but this can be partially explained by failures in some of the innovation mechanisms, such as firms' investment in research. Additionally, some inaccuracies of GDP's methodology might have contributed to this invisibility.

FIR application to the 4th IR allowed the ex-ante identification of potential General Purpose Technologies and Development blocks: The *Intelligent & Materials development block* and the *Advanced Human development block*.

1. KEY WORDS

Energy, Technology, Institutions, Economic history, Industrial revolution, Fourth Industrial revolution, Energy transitions, Exergy, Energy Services, General Purpose Technologies, Development Blocks.

2. INTRODUCTION

The 4th IR is based on the introduction of Artificial Intelligence, Advanced Analytics and extensive Automation and Robotics. It differs substantially from previous revolutions because it allows and extend fusion of these new technologies and interactions across the physical, digital and biological systems (Schwab, 2016; pg.8).

The research question: "How can understanding the past three Industrial Revolutions help industry prepare for the 4th Industrial Revolution, maximizing its upside and minimizing its downside?" is addressed through a systematic analysis of the past industrial revolutions, for which a framework was developed: The Framework for Industrial Revolutions, FIR. This was developed based on historical/technical observation, and it differentiates itself from other approaches by being both concise and encompassing the key factors that contribute to the clarification of some of the complex interactions between technology, energy and institutions, in the past and in the future.

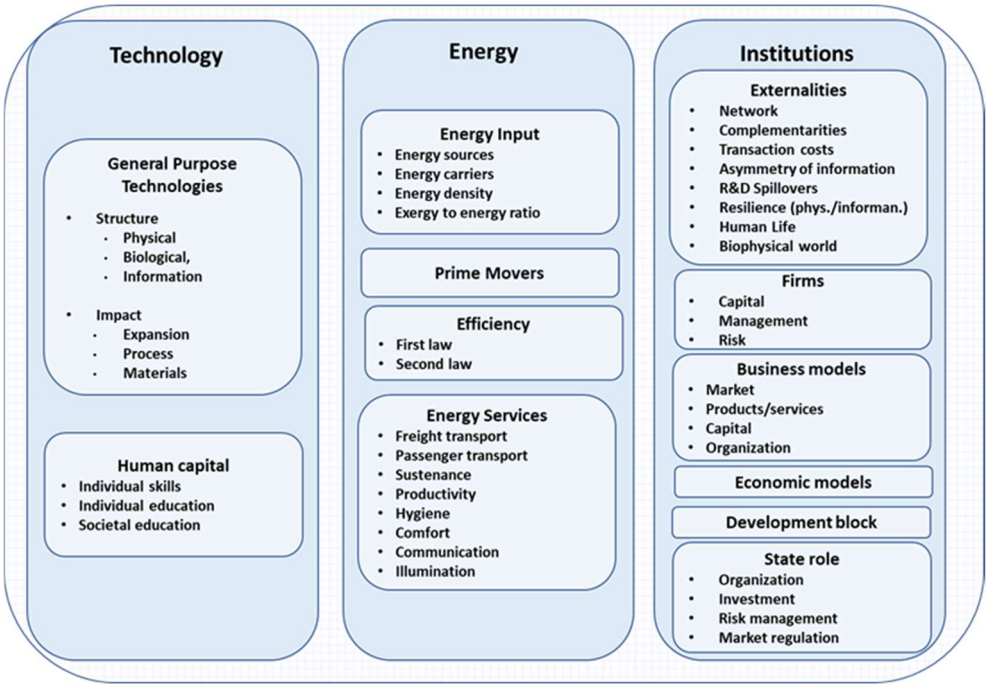
FIR goes beyond Kander (2013), Gordon (2016) and North (1990), by integrating the three components which are specific to each, i.e., energy (Kander, 2013), technology (Gordon, 2016) and institutions (North, 1990). After applying it to past industrial revolutions, the findings are used to address the 4th IR. To test FIR's utility to specific complex problems it was applied to the stagnation of economic growth.

3. METHODOLOGY

FIR encompasses three main topics of analysis: Technology, Energy, Institutions.

These topics emerged from the historic and technical analysis and were selected due to their relevance as industry descriptors: **Technology** is the mechanism by which society transforms raw materials into useful output (products and services) by using **Energy** and **Institutions** is the enabling factor that supports or undermines these processes. Although being obtained independently from economic theory, FIR presents an interesting integration and expansion of different economic theories such as the neoclassical and the institutional ones.

Figure 1 – FIR



FIR is the materialization of the economic historian Joel Mokyr's theory (2009, pg.12): *"The economic game is played at two levels: the level of a game against Nature (technology), and a game of interacting with other people (institutions)".* In FIR I propose to consider Technology and Energy as the key components of the *"…game against nature…",* and Institutions as the key component of the "…*game of interacting with other people…*".

4. 3.1 FIR TECHNOLOGY

FIR begins to address **Technology** which is composed by the *"…physical component which comprises of items such as products, tooling, equipment, blueprints, techniques, and processes"* and the *"informational component which consists of know-how in management, marketing, production, quality control, reliability, skilled labor and functional areas"* (Wahab, 2012, pg.2).

So, the **Technology** topic includes both the physical (material) and the informational (immaterial) components, and contains:

- **General purpose technologies** which *are "…a single generic technology, recognizable as such over its whole lifetime, that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects."* (Lipsey, 2005, pg.8).
  Examples of GPT are: steam engine, internal combustion engine, electricity, computer, internet.
- **Human Capital** - *…human capital represents the stock of skills, education, competencies, and other productivity-enhancing characteristics embedded in labor…"* (Becker *et al* in Court, 2018, pg. 22).

General Purpose Technologies (GPT) is a single technology, it is a kernel of development that starts an innovative process having the GPT as a fundamental piece. GPT is the basic technology at the top of a technological hierarchical tree and is characterized by:

- **Generality of purpose** (Bresnahan, 1992, pg.10);
- **Not having clear substitutes** (Bekar *et al*, 2017, pg. 1009);
- **Pervasiveness**, that is, used as inputs in many downstream sectors (Bresnahan, 1992, pg.0);
- **Wide scope of improvement** and elaboration (Lipsey, Bekar *et al* in David, 2003, pg.144);
- **Applicability** across a broad **range of uses** (Lipsey, Bekar *et al* in David, 2003, pg.144);
- **Strong complementarities** with existing or potential new technologies (Lipsey, Bekar *et al* in David, 2003);
- **Initially crude but evolving in complexity** (Bekar *et al* l, 2017, pg. 1009);
- **Potential** for **use** in a wide **variety** of **products** and **processes** (Lipsey, Bekar *et al* in David, 2003, pg.144);
- A role as **facilitator** for **spreading innovation** by *"…the invention and production of new products or processes"* (Grossman *et al* in Mazzucato, 2015, pg.68).

FIR also addresses **Human Capital** – *"…human capital represents the stock of skills, education, competencies, and other productivity-enhancing characteristics embedded in labor…"* (Becker *et al* in Court, 2018, pg. 22) Human capital is *considered "the stuff that enables people to earn a living"* (Bishop, 20014). FIR focuses on individual skills, on education and on the societal possibilities of knowledge/skills transmission.

5. 3.2 FIR ENERGY

Under the Energy topic, FIR includes **Energy Input**, **Energy Prime Movers**, **Energy Efficiencies** and **Energy Services**.

Energy Input comprises **Energy Sources**, **Energy Carriers**, **Energy Density** and **Exergy to Energy ratio**.

The **Sources of Energy** are the natural forms of energy, which, either directly or through transformation, become **Energy Carriers**. The latter can deliver **Energy Services**, such as heat, transport, illumination.

Energy Sources are the Primary Energy *"…the energy that is embodied in resources as they exist in nature: chemical energy embodied in in fossil fuels (coal, oil and natural gas) or biomass, the potential kinetic of water drawn from a reservoir, the electromagnetic energy of solar radiation, and the energy released in nuclear reactions."* (GEA, 2012, pg. 103).

For **Energy Carriers** the definition used in this work is "*Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes"*. (ISO, 1997). Examples: springs, electricity, electrical batteries, gasoline, jet fuel, or heating oil, etc.

Energy Density is the amount of energy per unit mass of a resource (Smil, 2017, pg. 9) for solids and liquids.

The **Exergy to Energy ratio** is the quality factor of an Energy carrier; once multiplied by the Energy content gives the Exergy content (Wall, 1987, pg. 59), (Ayres et al, 2003, pg. 959). *"Exergy is defined as the maximum amount of energy that under given (ambient) thermodynamic conditions can be converted into any other form of energy; it is also known as "availability" or "work potential."* (GEA, 2012, pg.117).

Energy Prime Movers' are machines that convert primary or energy carriers into mechanical work.

The **First-Law efficiency** or Energy efficiency[1] (η) (Nakicenovic 1989, pg. 150) is defined as the ratio of the desired (usable) energy output to the energy input (GEA, 2012, pg. 116). **Exergy**[2] **efficiency** or **Second-Law efficiency** (ε) is *"...the ratio of the theoretical minimum amount of available work or exergy needed to perform a particular function to actual available work or exergy consumed by a particular device or system to perform the same function."* (Nakicenovic 1989, pg.184).

Exergy is the maximum theoretical work obtainable from a system as it comes into equilibrium with the environment (Moran, 2012, pg. 330).

Energy Services[3] are those functions performed using energy which are means to obtain or facilitate desired end services or states (Fell, 2017, pg. 137). Examples: heating, cooling, lighting, cooking, etc.

Cullen & Allwood (2010) propose a classification for **Energy** (final) **Services**: thermal comfort, sustenance, structure, freight transport, passenger transport, hygiene, communication and illumination. In FIR **Energy Services** are classified in: Freight transport; Passenger transport; Sustenance (includes nourishment, health); Productivity (work related); Hygiene; Comfort (thermal, psychological visual); Communication; Illumination. FIR introduces one additional category (beyond Cullen and Allwood, 2010), in. *Productivity*, that is related with the execution of work or the support of working activities. *Comfort* used in FIR has a wider scope than the thermal comfort used by Cullen & Allwood (2010), namely by including hedonism.

6. 3.3 FIR INSTITUTIONS

In this work **Institutions** are all the social structures in society that *"…reduce uncertainty by providing a structure to everyday life."* (North, 1990; pg.3), establish explicit and implicit norms and rules, place limits and support activities.

The **Institutions** topic of FIR comprises: **Externalities**, **Firms**, **Business Models**, Economic Models & Development Blocks and **State role**.

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[1] **Energy Efficiency**: η = Energy output in product/Energy input = 1 − [Energy loss/Energy input] (Dincer, 2007, pg. 14).

[2] **Exergy Efficiency**: φ = Exergy output in product/Exergy input = 1 − [Exergy loss/Exergy input] (Dincer, 2007 pg.14).

[3] "**Energy Services** are the result of a combination of various technologies, infrastructure (capital), labor (know-how), materials, and energy forms and carriers." (GEA, 2012, pg.103), also "*Energy services (…) relate to services that traditionally required large amounts of energy for provision*." (Fouquet, 2008, pg.8).

Externalities *"…exist[s] whenever the welfare of some agent, either a firm, or a household, depends not only on his or her activities, but also on activities under the control of some other agent."* (Tietenberg, 2012, pg.25). Externalities can be originated by:

- Networks in which *"a one person's consumption directly influences another person's utility"* (Varian, 2010, pg.678);
- Complementarities in which "*the value of one component is significantly enhanced by the presence of another component"* (Varian, 2010, pg.668);
- R&D spillovers (Mazzucato, 2015, pg.208);
- Asymmetry of information, when some players have more information than others (Krugman, 2013, pg.585);
- Transaction costs, i.e., the costs of defining, protecting and enforcing property rights (Wiliamson in Ankarloo, 2006);
- Pollution (Krugman, 2013, pg.459).

Institutions were included in FIR acknowledging their contribution to the comprehension of economic and social change (North, 1990, pg.3), and their impact on the economic performance of societies (Chang, 2011) (North, 1990, pg.113,130). Institutions exist and persist due to the positive externalities they generate and maintain. Institutions, together with technology, establish the transaction and production costs of an economy (North, 1990, pg.3).

In FIR, externalities are classified according to their occurrence:

- Information - Knowledge related – education, know-how transfer;
- Social structures – Firms, State infrastructures, State regulations, professional associations, kinship, etc.,
- Human centered - Human physical and mental wellbeing
- Biophysical externalities - the impact of human activity on natural ecosystems and natural resources

Firms are *"… an organization which sells or produces something or which provides a service which people pay for."* (Collins, 2019). According to Coase (1937), the economy does not rely only on market transactions, and he explains it by the existence of externalities. Coase defends the existence of firms based on the reduction in transaction costs they induce. That is, firms emerge when it is economically more efficient for the entrepreneur to maintain a continuous contractual relation – hiring – of services or products, instead of contracting via the market (Coase, 1937).

Firms operate according to their business model (organization level), generating, capturing and delivering value integrated in a bigger framework: their economic model (system-level) (Bent, 2019). The economic model differs from the business model in the scale, scope, objective and advocates. The economic model has a societal scale, that can be sectoral, national, regional, it might integrate several companies, and should have the objective of increasing societal welfare. Usually the objective of the firm is to maximize shareholder value and its stronger advocates are usually management and shareholders. Shareholders are the owners of the capital of a firm, whereas Stakeholders are all the firm's interested parties; these can be clients, suppliers, workers, shareholders, creditors, bondholders, the State and citizens (Bishop, 2004).

Firms are viable in the short term when their business model produces private value, and firms are sustainable in the long run when their economic model produces net positive externalities[4] (i.e., positive minus negative externalities), i.e., their activity contributes to increasing social welfare, beyond the private value created.

[4] Positive externalities in Business models result from savings in (repetitive) contract negotiation, in economies of scale in processes, in labor specialization and labor division (Coase, 1937).

Firms optimize their private value generation by having a good strategy, generating revenues, reducing costs and managing adequately the Firm's risks.

In FIR Firms are characterized by their Legal denomination, their Capital structure, their overall Management structure and how they address Firm Risk Management.

Business Models will be used to explicit how firms function to generate, deliver and capture value in all dimensions: economic, financial, social, cultural and environmental. Firms do so by the smart choice of the products/services they provide, their capital and their organization.

Economic Models will be used to explicit how a society functions to generate, deliver and capture value in all dimensions: economic, financial, social, cultural environmental. Economic Models here have much in common with Economic Systems, that are *"…a set of institutions for decision making and for the implementation of decisions concerning production, income, and consumption within a given geographic area."* (Gregory *et al*, 2013; pg. 25). In FIR, Economic Models have a system scale, i.e., national or regional, and are characterized by their Market Structure and their Coordination Mechanisms. In the literature Economic Models have other dimensions (Gregory *et al*, 2013; pg. 25) that were not considered relevant to be addressed in FIR

The Market Structure concentrates on the structural characteristics of the markets, i.e., whether they are local or regional or global, urban or rural, etc.

The Coordination Mechanisms addresses the way in which society is organized, if it is a planned economy, if there are policies to fund business, to support new markets, etc.

Development Blocks are defined by Dahmén as *"…a complementary relation or a positive externality between industries, firms, and plants where innovations or investments are concerned"* (Erixon, 2011, pg.112). Usually a development block begins with one or more macro-innovations and develops with *"... a series of further micro-innovations, and possibly meso-innovations to widen its application, and adapt complementary technologies to be used in combination with it."* (Kander, 2013, pg.28). Examples of *Development Blocks* are: Coal and Iron *Development Block*, Steam Engine *Development Block*, Rail *Development Block*, Internal Combustion Engine *Development Block*, Electricity *Development Block*, Information and Communication Technology *Development Block*, etc.

The Development Block has the scale of an economic model and can be detected qualitatively through the recognition of positive externalities among sectors, industries, firms, translated into positive marginal returns, and quantitatively by applying co-integration statistical analysis and short-run Granger causality tests (Enflo, 2003). The existence of Development Blocks originates backward and forward linkages (Kander, 2013, pg.232).

The Development Block is a concept from industrial economy that was first enunciated by Dahmén (Enflo, 2006). Development blocks are the result of positive externalities (Erixon, 2011, pg.112), such as complementarities (Enflo, 2006):

> *"Innovations create new complementarities—i.e. they create new dependencies between specific functions or properties within the production process or between production and infrastructure or institutions. New competencies, new firms and new branches come to the fore. (…) When the complementarities are complete, the factors within a block mutually increase their marginal returns and productivity is enhanced."*

Development Blocks are usually associated with the industrial era, being at the core of industrial development: but these structures – chains of processes that appear and persist due to the positive externalities that they

originate have been around since much earlier than the industrial era, e.g.: The Iron development block, The Wheel development block, etc.

Although Kander states that "*Sometimes, but not always, this [*Development Block*] also takes the form of a general purpose technology..."* (Kander, 2013, pg.29), in this thesis, it is considered that GPT are the core technologies acting as seed, from which Development Blocks - the economic, industrial, and social systems – develop. A GPT can participate in different Development Blocks, for example, electricity participates as a GPT in several Development Blocks such as the rail Development Blocks, the information and communication technology (ICT) Development Blocks, etc.

The identification of the GPT and of the associated (existing or probable of future occurrence) Development Block is very important to develop economic systems (economies and businesses). It is proposed in this work that businesses and the State should identify embryonic development blocks and step in. The early participation in an expanding development block gives access to an expanding system of increasing marginal returns, and positive externalities. The proposed methodology to identify the Development Block comprises:

1. Are they generated by at least one GPT?
2. Do they originate complementarities?
3. Do they cause positive externalities among the *development block* components?
4. Are there forward and backward linkages among the components of the *development block*?

The **State role** focuses on how the State envisions and shapes society, namely by influencing social and economic structures, through an effective rule of law, by correcting market failures, by defending collective desires, by promoting well-being and social inclusion. This is achieved through strategic public policies, i.e., allocation of public resources, such as public funding, territorial planning, education, etc., through fiscal policies, includes taxes and subsidies, and others like public procurement, information management, among others. (Baldwin, 2012, pg.3).

In FIR, State addresses all the public sector institutions, i.e., municipalities, public authorities, government. This nomenclature is aligned with Mazzucato (2015). State institutions emerge from the social contract with the constituents, in which they provide the funds to operation and in return get representation that enables them to decide on policies through their representants in parliament[5] (North, 1990; pg.113). The State originates positive externalities when it provides coordination, justice, property rights enforcement, societal infrastructure, healthcare, education, security, last resort insurance, among others

FIR considers the main contributions that the State provides: Organization, Investment, Social Risk Management and Market Regulation. In the Investment contribution the State role includes innovation development, infrastructure development and education. Firm Risk Management differs from State Social Risk management on objectives and methods. Firm Risk Management is concerned with the Firm's assets and cash flow's integrity, whereas the State Social Risk management is concerned with potential changes that might affect present and future social welfare in a country or a region.

7. RESULTS

FIR has identified the introduction of energy sources, and its qualities, such as energy density, second law efficiency as important factors to explain the first two IRs. On the other hand, in the 3rd IR there is no introduction

[5] In his book North (1990) uses the term "Government", this was modified to "State" in the present text to guarantee nomenclature coherence.

of a new energy source, or any process that changes substantially energy efficiency. Also, apparently, in the 3rd IR the technology introduced had not such a visible effect, but this can be partially explained by failures in some of the innovation mechanisms, such as firms' investment in research. Also, some inaccuracies of GDP's methodology might have contributed to this invisibility.

FIR application to the 4th IR allowed the ex-ante identification of potential GPT and of potential Development blocks: The Intelligent & Materials development block Figure 2) and the Advanced Human development block (Figure 3).

The 4th IR presents a larger number of potential GPT than the previous IRs. This opens the door to the existence of much more development blocks beyond the two proposed ones. The existence of a larger number of potential GPT might also explain the forecast dramatic impact of the 4th IR technologies.

When applied to the 4th IR, FIR identified the need to massively upgrade workers skills and the important role that Firms, the State and the Universities must collectively play on it.

Figure 2 – Intelligent & Materials development block

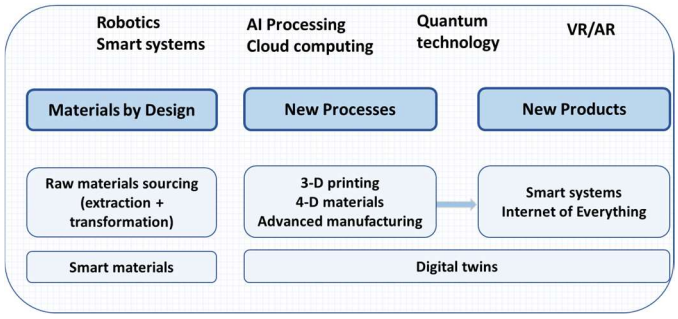
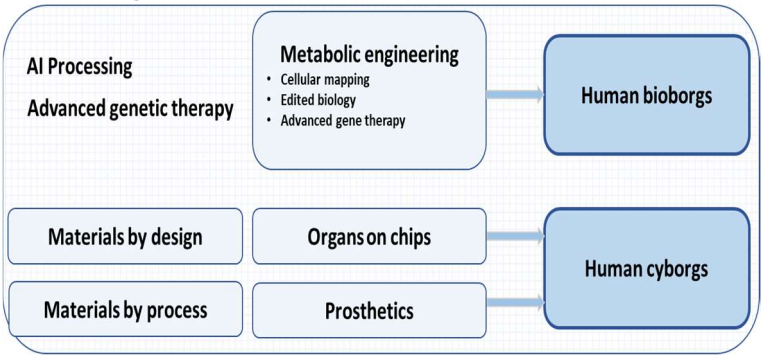


Figure 3 – Advanced Human development block



FIR was applied to the stagnation of growth in developed western economies trying to reconcile the current views about growth: the techno-pessimists that defend growth will never achieve previous levels due to the exhaustion of technological development possibilities (Gordon, 2016, pg.320), the techno-optimists (Mokyr, 2009, 2016, 2018) (Brynjolfsson et al, 2014) (Kurzweil, 2006) that defend it is a moment and growth will return and a third view that defends growth will increase in the presence of adequate political, strategic and social measures (Mazzucato, 2015), (Piketty, 2014), (Jacobs et al, 2016). From the application of FIR to the stagnation of economic growth that has been occurring in the end of the 20th century it can be concluded that the financialization of economy, an institutional factor, might be a key explanation.

8. CONCLUSIONS

Besides its widespread utility, FIR presents more merits, such as being originated by the thorough study of seven millennia of historical, technological, economic and energy facts. This has provided FIR with some ingenuity as well as with its structure and extensiveness.

FIR emerged from the search for a systematic approach that has arisen from the necessity of new tools to address the 4th IR., which being a disruptive change in the civilizational paradigm needed to be addressed in a completely different way, namely in a multidisciplinary, simultaneously specialized and global approach.

FIR is a coherent and useful tool in analyzing societal transformations. By means of encompassing the three key factors: technology, energy and institutions, FIR has contributed to the understanding of the past revolutions, as well as it has proven useful in complex and transformational phenomena, such as the stagnation of economic growth in western economies after the 1970s.

FIR is coherent with pre-existing theories, namely Kander (2013), Gordon (2016) and North (1990) but is more comprehensive, it differentiates itself by integrating energy (Kander, 2013), technology (Gordon, 2016) and institutions (North, 1990).

FIR has identified the introduction of energy sources, and its qualities, such as energy density, second law efficiency as important factors to explain the first two IRs. On the other hand, in the 3rd IR there is no introduction of a new energy source, or any process that changes substantially energy efficiency. Also, apparently, in the 3rd IR the technology introduced had not such a visible effect, but this can be partially explained by failures in some of the innovation mechanisms, such firms' investment in research. Some inadequacies in GDP's methodology might also have contributed to this situation.

FIR application to the 4th IR allowed the ex-ante identification of potential GDP and of potential Development blocks: The Intelligent & Materials development block (Figure 2) and the Advanced Human development block (**Error! Reference source not found.**).

The 4th IR presents a larger number of potential GPT than the previous IRs. This opens the door to the existence of more development blocks beyond the two proposed ones. The existence of a larger number of potential GPT might also explain forecasted dramatic impact of the 4th IR.

When applied to the 4th IR, FIR identified the urgent need to massively upgrade workers skills, and the important role that Firms, the State and the educational system, in particular Universities must collectively play on it.

From the application of FIR to the stagnation of economic growth since the 1970s it can be concluded that a key factor was an institutional one: the financialization of economy and the failure of society in addressing it.

From a systematic approach FIR contributes to the clarification of roles and duties, namely for Firms, the State and the workers. Firms should recover the role they had until 1970, providing traction to economy by being wealth redistributors: through the investment in innovation that allowed technology development, the investment in workers welfare improvement through social benefits, education and rising wages (real). The State should be empowered and held responsible for its roles: societal organization, investment, risk management and market regulation. The workers have the responsibility to contribute to productivity, either by their commitment and performance either by achieving new and useful skills.

FIR provides a systematization for an early identification of potential GPT and the consequent backing of the related Development blocks. These should be supported by the State and the Firms, in line with the economic, social, technological and environmental strategic policies established.

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