The Effects of Innovation on Well-being: A Conceptual Framework

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2023

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This version: May 2025

Abstract

Innovation affects human well-being in a complex variety of ways. The economics of innovation has typically focused on the positive economic impacts that new technologies have on well-being through income growth and consumption dynamics, and often neglected a variety of other non-economic and negative effects. This paper presents a broad conceptual framework of innovation and well-being that seeks to combine economic and non-economic impacts, positive as well as negative, into a comprehensive agent-based model (ABM). The ABM investigates well-being determinants and dynamics for a population of heterogenous agents. I empirically calibrate the model for the US economy. The aggregate long-run outcomes of the model are stagnant average well-being *cum* increasing disparities between rich and poor individuals. The key novelty of the framework is that it points out seven distinct effects of innovation, and it shows that these mechanisms have different relevance for the well-being of individuals. The paper combines insights from different strands of research at the intersection between the economics of innovation and well-being studies, and it points out directions for future research on this topic.

Key words: Innovation; well-being; agent-based model

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1 Introduction

Innovation has contributed to terrific improvements in well-being over the history of humankind. This has been a major underlying motivation for the development of research in the economics of innovation, and for the establishment of innovation policy as a new public policy domain (Witt, 1996; Nelson, 2011). However, behind the general agreement that new technologies matter for social welfare, innovation research and policy have not yet achieved a detailed and comprehensive understanding of the complex set of factors and processes that link innovation to the well-being of individuals (Martin, 2016).

In fact, when we look at empirical data, the correlation between innovation and well-being, that we often take for granted in academic research and in policy-making, is far from clear. Consider for instance the US, which has for many decades been the world's technological leader economy. As documented in Table 1, innovations developed in the US (measured by the number of patents per capita) have grown by more than 300% during the last four decades. Nevertheless, in the same period, the average well-being of the population (measured by feelings of happiness and life satisfaction reported by individuals in well-known large-scale surveys) has increased only marginally, and if we consider a more recent period it has even slightly declined. Why is this the case? Shouldn't we expect to see a closer correlation between the development of new technologies and advances in human well-being over time?

Table 1: Innovation and well-being in the US (selected indicators), total growth for the period 1980–2020

Innovation	Patents per capita[a]	+330%
	Happiness level[b]	+4%
Well-being	Share of happy people[c]	+6.2%
	Life satisfaction[d]	−4%

[a] Patents granted by USPTO, 1980–2020 (source: USPTO).
[b] Feeling of happiness, 1980–2008 (source: World Values Survey).
[c] Share of happy people, 1980–2020 (source: General Social Survey).
[d] Life satisfaction, Cantril ladder scale, 2005–2020 (source: Gallup World Poll).

To explain the relationship between innovation and well-being, the standard and traditional approach in the economics of innovation is to posit that new technologies support individuals' well-being by fostering income growth, which in turn enables the consumption of new varieties and thus the satisfaction of new preferences. This argument is paramount, but it provides an incomplete and biased picture of the complex relationship between innovation and well-being (Castellacci, 2022).

The argument is incomplete because it focuses on relevant economic factors, but it neglects a variety of other dimensions, which are by definition non-economic, and that are known to be important determinants of well-being. For instance, technological and organizational innovations may affect the quality of workplace, working and social relationships, family life, as well as the physical environment and socio-institutional environment in which agents live. Many of these dimensions cannot be measured by means of monetary metrics only, and they have often been neglected in the economics of innovation (Bozeman and Sarewitz, 2011).

Further, the standard and traditional understanding of well-being in innovation research is also biased, because it has so far mostly focused on the positive effects that innovation has on economic performance (GDP, productivity, competitiveness, employment, consumption), and often neglected the negative effects and possible risks that some innovations lead to – what recent research calls "the dark sides of innovation" (Biggi and Giuliani, 2021).

These two criticisms to the standard understanding of the innovation – well-being relationship call for a deeper understanding of the complex set of mechanisms that underlie this relationship, and that may contribute to explain the empirical paradox illustrated in table 1. While it is true that innovation fosters well-being by sustaining economic growth and consumption possibilities, it may be the case that technological change also has some negative impacts on individuals' well-being that standard economic models neglect, and that may counteract and partly offset the related positive effects. Hence, the patterns that are shown in table 1 may represent the aggregate result of a complex set of diverse mechanisms by which innovation, and different types of innovations, affect individuals' well-being.

This topic is not only relevant for the economics of innovation, but it may also be important for the broader interdisciplinary community in innovation studies. In the last few years, the innovation literature has considerably broadened up its scope, and begun to investigate a variety of other impacts of innovation on social welfare, and how innovation policy may contribute to address a variety of societal objectives that go beyond the mere achievement of economic performance. The recent normative turn in innovation studies is motivated by the general belief that innovation should contribute to create public value and inclusive outcomes, and lead to a sustainable and just transition (Bozeman, 2020; Ciarli et al., 2021). The achievement of these socially desirable outcomes calls for active public policy efforts and directionality in innovation policy (Haddad and Bergek, 2023). However, this recent literature implicitly views social welfare, social progress and societal challenges as aggregate concepts (referring to a nation, population or innovation system), and typically neglects the study of their key microfoundation: individuals' well-being. If innovation must address societal challenges, I argue, it is also important to develop a thorough understanding of how it affects the well-being of different agents and social groups that compose a given population or innovation system.

Motivated by these criticisms to the narrow notion of well-being in the economics of innovation, and more in general the lack of attention that innovation studies have so far devoted to the study of well-being, the present paper argues that, if we want to advance our understanding of the links between innovation and social welfare, it is paramount to adopt a broader definition of individuals' well-being, that enables the inclusion of a variety of factors and determinants in addition to consumption and material wealth.

This calls for cross-fertilization between two fields of research that have so far had scant interactions with each other: the economics of innovation, on the one hand, and well-being studies, on the other. Well-being studies point out two relevant dimensions that contribute to shape human well-being (Adler and Fleurbaey, 2016). The first is *subjective well-being*, which is well-being as perceived by each individual, and that has both an emotional (hedonic) and an evaluative dimension (Clark and Senik, 2010; Kahneman and Deaton, 2010). The second is *objective well-being*, which refers to the attainment of objective goods which enable individuals to achieve key capabilities and functionings and so conduct a good and decent life (Sen, 1985; Graham and Nikolova, 2015; Alkire, 2016). The present paper takes as a starting point the argument that, since innovations have so diverse and multifaceted effects on well-being, the study of this relationship must adopt a broad notion of well-being that includes both of the dimensions noted in the literature

(Piacquadio, 2017; Castellacci, 2022). This makes it possible to consider economic and non-economic factors, positive as well as negative, within the same conceptual framework.

To provide a comprehensive conceptual framework to study this topic, the paper presents an agent-based model (ABM) of innovation and well-being. The reason for choosing an ABM approach is that this modelling framework is quite flexible: it makes it possible to investigate a broad variety of different mechanisms linking innovation to well-being, point out different patterns for different individuals and social groups, and study aggregate long-run outcomes as emergent properties of agents' behavior. *The purpose of the model is to build up a comprehensive conceptual framework that points out all diverse effects that technological innovations may have on well-being.* This framework may be used, applied and extended in a variety of directions in future research. Model extensions, modifications and empirical applications to study specific technological trajectories may be the subject of future research (as it will be discussed further in the concluding part of the paper).

The ABM model investigates well-being and its determinants in a population of heterogenous agents. Individuals are heterogenous in terms of financial capital endowment and education and skill levels, and at any period they allocate their time between work, leisure, and education and skill formation. Time allocated to work and leisure increases work and leisure well-being, respectively, at present; whereas time spent on education and training activities will foster skill and wage dynamics, and thus lead to further well-being, in future periods. When innovations are introduced in the economic system, agents start to use them. Technology adoption is endogenous, and it depends on each agent' skill level as well as the number of peers that have already adopted the same technology (Zeppini and Frenken, 2018). I empirically calibrate the model to reproduce major macro trends and stylized facts for the US economy in the period 1980-2020. Simulation analysis shows that, in the long-run, the model generates increasing GDP per capita and stagnant well-being for the whole population, but it also leads to polarization patterns and increasing disparities in well-being between rich and poor individuals.

The key aspect of the model is that it focuses on how innovations affect different aspects of well-being. Specifically, the ABM points out *seven different types of effects of innovation on well-being.* The model argues that all innovations that we may think of affect individuals' well-being through one or more of these seven mechanisms. Importantly, the theoretical framework shows that the various effects of innovation have different relevance for the well-being of individuals, some being clearly more relevant and lasting than others.

The general theoretical framework that is presented in this paper contributes to extant research on innovation and well-being (Dolan and Metcalfe, 2012; Binder, 2013; Engelbrecht, 2014; Nikolova et al., 2024). This research is scant and fragmented. It is scant because it has so far mostly focused on digital technologies and some of their effects on users' well-being (Kavetsos and Koutrumpis, 2011; Penard et al., 2013; Castellacci and Schwabe, 2020; Nikolova et al., 2024), but it has neglected several other potentially relevant mechanisms that this paper will consider. This research is also quite fragmented, since different strands of studies on this theme are developing within different fields – such as the economics of innovation, well-being studies, behavioral economics and psychology – and without much cross-fertilization and mutual interaction (Castellacci and Tveito, 2018). This paper intends to contribute to extant research by providing a new broad conceptual framework that will bring together relevant insights from different strands of research and guide future studies.

The paper is organized as follows. Section 2 presents the structure of the ABM model. Section 3 presents information on the empirical calibration of the model, and its dynamics and outcomes. Section 4 presents the core part by pointing out the seven mechanisms that link innovation to well-being. Section 5 points out the key result of this analysis, and discusses its implications for future research. Section 6 concludes the paper, highlights its contribution to academic literature on the subject, and points out its normative implications.

2 The model

The ABM describes a population of N heterogenous agents. Each agent lives for T years (from birth to death). During the life cycle, an agent spends time in three different ways: investing in human capital and skills, working to earn an income, and enjoying leisure and social life.

At time t, agent i's well-being (utility) is the sum of well-being derived from two domains of life: work (W) and leisure (L):

$$U_{it} = aU_{it}^{(W)} + (1-a)U_{it}^{(L)} \tag{1}$$

Parameter a measures the relative importance of the two domains of life. The model posits that the parameter is the same for the whole population, reflecting cultural and social values (e.g. materialistic culture versus collective society) that characterize a country in a given historical period.

Well-being in working life. This is defined as:

$$U_{it}^{(W)} = b(1-\varepsilon)Y_{it} + cY_P + dY_{i,t-1} + ePE^{(W)} + fSE^{(W)} \tag{2}$$

The first term on the right-hand side shows that an agent's utility derived from working life at time t is positively related to the absolute income Y that it earns (net of education costs, defined below). Parameter b measures the importance of absolute income for utility; while parameter ε denotes the saving propensity; thus, $(1-\varepsilon)$ is the fraction of income that is consumed in each period.[1]

The second term represents so-called *relative income effects* (Senik, 2005; Clark and Senik, 2010). This term indicates that an agent's well-being is negatively related to the average income of its peers (Y_P), since individuals experience an increase in utility (disutility) when their own income increases (decreases) *vis-à-vis* that of their peers: (Y_P):

$$\frac{\partial U_{it}^{(W)}}{\partial Y_P} < 0$$

Hence, parameter c measures the extent to which social comparisons affect well-being. The number of peers that each individual considers relevant for its own income comparisons (N_P) is δN, where δ is the fraction of agents in the population that are considered peers (or neighbors) of i ($0 < \delta < 1$). Thus, parameter δ defines the extent to which social proximity matters for social comparisons. For instance, in the corner case in which

[1] For simplicity, I disregard changes in prices of consumption goods, and assume that consumption, income and wages (defined in further details below) are all measured in real terms. Hence, the model assumes that an increase in prices would translate into an equal increase of wages, such that real wages and real income are not affected by price changes.

$\delta = 1$, individuals assess their relative income by comparing it to the average income of the whole population.

The third term on the right-hand side of the equation notes so-called *adaptation effects*, representing the idea that individuals tend to quickly adapt to a given level of income and consumption (Shafir, 2016). Specifically, this means that an increase of income at time *t-1* will lead to a less than proportional increase in well-being at time t, because a fraction of this increase will be discounted, or lost, due to "habituation":

$$\frac{\partial U_{it}^{(W)}}{\partial Y_{i;t-1}} < 0$$

Hence, based on well-being empirical research, parameter d is expected to be negative, since it measures the extent to which adaptation mechanisms negatively affect well-being (Baggio and Papyrakis, 2014).

Finally, the fourth term points out that utility from work is also positively related to the quality of the physical environment at work $PE^{(W)}$, and the quality of the social environment (social capital) at work $SE^{(W)}$ (Castellacci and Bardolet, 2018). Parameters e and f measure the importance of these work-environmental aspects for job satisfaction. I assume that these are country-level parameters that are the same for all agents in the population.

Gross income that is earned at work is the product of the amount of working time spent by each individual in period t ($T_{it}^{(W)}$) and its wage level W:

$$Y_{it}^{G} = \left[T_{it}^{(W)} \cdot W_{it}\right] H_{it} \tag{3}$$

As noted in equation 3, gross income $Y^{(G)}$ is also affected by H, which denotes health conditions. H is a dummy variable that takes value 1 if an individual is healthy (thus working full-time), or value $\theta (0 < \theta < 1)$ if the individual is sick (thus working only on a part-time basis, and/or receiving public care benefits). In any period, a fraction of agents is sick (according to a random function that is further defined below), whereas all other agents are healthy and full-time working (for simplicity, I disregard unemployment in this model).

$$W_{it} = g \cdot S_{it} \tag{4}$$

Wage W is a function of the individual's skill level S and the parameter g, which measures the extent to which an increase in the skill level leads to a wage increase (thus reflecting the skill premium, as well as labor market institutions that affect wage formation mechanisms).

Skills and human capital dynamics. Over time, individual skill level S may increase as a function of two factors:

$$S_{it} = S_{i,t-1} + h\left[T_{it}^{(S)} \cdot K\right] \tag{5}$$

The first is K, that denotes "knowledge capital", i.e. the amount of information that is publicly available to agents, and that they use to carry out their productive activities and to choose their leisure activities. K is assumed to be an exogenous factor (e.g. representing the publicly available information that individuals have from the media and the Internet). The second factor is $T^{(S)}$, which is the time that an agent allocates to education and skill formation in a given period. The extent to which K and $T^{(S)}$ increase an agent's skills depends on the parameter h, which represents how easy/difficult it is to increase skills over time.

The model assumes that young agents ($AGE < A^*$) spend all of their productive time (excluding leisure time) studying, whereas adult agents ($AGE > A^*$) mostly work to earn an income, but they may also allocate a fraction of their working time to further education and training activities in order to get a higher salary level in the future. If an agent allocates time to investment in human capital in a given period, this will increase its skill level permanently from the next period onward (the time allocation rule is discussed further below).

Every time an individual invests to increase its skill level S, it incurs the fixed education fee F_s. The cost of education is financed by individuals by using own financial capital C_{it}, if available. Education expenditures F_s reduce net income Y_{it} that an individual can devote to consumption and preference satisfaction in a given period. If capital endowment C is not available or exhausted, the individual cannot invest any longer in education, and must simply work full-time.

Financial capital. Allocation of financial capital C_{it} is heterogenous among individuals. For the first cohort of agents, financial capital is distributed randomly. Subsequently, when agents grow and have kids, each new-born receives an initial endowment of financial capital C_{it}, which is the same as his parents' (representing the idea that kids of rich families have higher capital and can afford more education than kids of poor families). Hence, agents are heterogenous in terms of capital endowments (inherited from their families), and therefore in terms of the amount of education that they are able to finance during their lifetime. Richer (poorer) individuals can afford more (less) education, and therefore are more likely to have higher (lower) skill and wage levels during their lifetime. In every period, an agent may save a fraction ε of income (saving propensity), and this saving increases its financial capital over time, thus partly offsetting the reduction of capital due to investments in education.

Well-being from leisure. Utility derived from leisure and social life is positively affected by three factors:

$$U_{it}^{(L)} = l\, L_{it} + m\, PE^{(L)} + n\, SE^{(L)} \tag{6}$$

The first is the total amount of leisure L that an individual enjoys at time t. Parameter l measures the extent to which leisure activities lead to utility.[2] The second factor is the quality of the physical environment $PE^{(L)}$ where the individual lives. And the third is the quality of the social environment $SE^{(L)}$ (e.g. social capital; quality of social interactions). I assume for simplicity that $PE^{(L)}$ and $SE^{(L)}$ are country-specific variables that are the same for all agents in a given historical period (Layard, 2005). Parameters m and n measure the extent to which these environmental factors matter for the well-being that agents derive from leisure time.

Leisure L is generated through an individual leisure function whose main inputs are the agent's amount of leisure time $T^{(L)}$ and its skill level S:

$$L_{it} = [T_{it}^{(L)} \cdot S_{it}] \cdot H_{it} \tag{7}$$

Agents that devote a greater amount of time to leisure will enjoy a greater amount of

[2] For simplicity, similarly to the price of consumption goods, the model assumes that L is measured in real terms. Hence, if the price of L increases, wages and income would increase correspondingly, so that real value of L would not be affected.

leisure activities. The model posits that leisure is also positively related to the agent' skill level, which affects the ability of individuals to choose the most rewarding among several possible social activities. Further, equation 7 notes that the individual leisure function is also moderated by health conditions H. Similarly to what pointed out in relation to equation 3 above, H is a dummy variable that takes value 1 if an individual is healthy (thus working full-time), or value $\theta (0 < \theta < 1)$ if the individual is sick. If an agent gets sick, it will only be able to spend a fraction θ of its leisure time for social activities, thus reducing its well-being from leisure.

Health, death and birth. The probability to get sick is a positive random function of individual's age: the older the individual, the more likely it is that it might get sick:

$$Pr[H_{it} = \theta] = o \cdot AGE_{it} \tag{8}$$

The population-level parameter o measures the average probability to get sick, reflecting the state and advances of health science and technologies in a given country and at a given historical time. Similarly, the probability to die (D) is a positive random function of age:

$$Pr[D_{it} = 1] = p \cdot AGE_{it} \tag{9}$$

Parameter p reflects average life expectancy (country- and time-specific parameter). Adult agents can have kids (if $AGE > A^*$). The probability that a new agent is born (B) is a random function governed by the parameter q, which represents the fertility rate (country- and time-specific parameter):

$$Pr[B_{it} = 1] = q \tag{10}$$

Time allocation. In every period t, an agent allocates its total available time ($T^{(T)}$) between time devoted to productive activities (study or work; $T^{(P)}$), and time devoted to leisure activities $T^{(L)}$ (Rojas and Ibarra-Lopez, 2014):

$$T_{it}^{(T)} = T_{it}^{(P)} + T_{it}^{(L)} \tag{11}$$

The allocation of time between $T^{(P)}$ and $T^{(L)}$ is fixed at any time t, and governed by the parameter r:

$$T_{it}^{(P)} = r \cdot T_{it}^{(T)} \tag{12}$$

$$T_{it}^{(L)} = (1 - r) \cdot T_{it}^{(T)} \tag{13}$$

Parameter r represents the share of time that individuals spend for productive activities on average in a given historical period, and $(1–r)$ is the corresponding share of time that agents spend for leisure activities. This parameter is fixed at any given period, but it can change over time as a result of technological progress and productivity advances, as it will be discussed further in section 4.

Productive time $T^{(P)}$ is the sum of time spent at work to earn an income ($T^{(W)}$) and time devoted to investments in education and skill formation ($T^{(S)}$):

$$T_{it}^{(P)} = T_{it}^{(W)} + T_{it}^{(S)} \tag{14}$$

In every period t, an agent allocates its productive time $T^{(P)}$ between work and skill formation. If the agent has enough financial capital and can afford the costs of education ($C_{it} > F_s$), the time allocation is:

$$T_{it}^{(S)} = V_{it} \cdot T_{it}^{(P)} \tag{15}$$

$$T_{it}^{(W)} = (1 - V_{it}) \cdot T_{it}^{(P)} \tag{16}$$

The variable $V_{it}(0 < V_{it} < 1)$ determines the share of productive time that an individual devotes to each of the two activities. In every period, an individual faces a trade-off between investing time in education *versus* devoting time to work and earn an income. Investing time in education at t decreases working time and income in that period, but it will increase skills and wage in the next periods (as well as utility from leisure, given a greater ability to choose more rewarding leisure activities, see equation 7). Facing this trade-off, the individual will choose the optimal allocation V_{it} such that:

$$\frac{\partial U_{it}}{\partial T_{it}^{(W)}} = \frac{\partial U_{it}}{\partial T_{it}^{(S)}}$$

Using equations 1, 2 and 6, and calculating first differences with respect to $T_{it}^{(W)}$ and $T_{it}^{(S)}$, respectively, I derive the following optimality condition:

$$T_{it}^{(W)} - T_{it}^{(S)} = \frac{S_{i;t-1} + F_s}{h \cdot K} - \frac{(1-a) \cdot l \cdot T_{it}^{(L)}}{a \cdot b \cdot (1-\epsilon) \cdot g} \tag{17}$$

Expression (17) points out that an individual increases its time allocated to work *vis-a-vis* education when: (1) it is more costly to increase skills (parameter F_s), or more difficult to do so (inverse of parameter h); (2) the marginal benefits of skills for the utility from leisure are low; (3) the marginal benefits of consumption for the utility from work are high.

However, the optimal allocation of time (work *versus* education) that an individual chooses will change over the lifecycle. In fact, an implication of optimality condition (17) is that, as the skill level of an individual grows over time, the marginal benefits of education will decrease *vis-a-vis* the marginal benefits of work. Hence, as they get older, individuals will progressively choose more work and less education. The variable V_{it} (denoting the share of productive time that an individual devotes to work *versus* education) can therefore be expressed as follows:

$$V_{it} = \frac{v}{AGE_{it}} \tag{18}$$

Figure 1 (upper panel) illustrates the relationship between the optimal amount of time of work and education that an individual chooses over the life cycle, representing the idea that younger individuals must spend a greater fraction of their productive time in schooling and education, whereas older agents spend most of their productive time at work and progressively less time for skill and training activities.

Note also that in equation 18, v is a dummy variable that takes value 1 if the agent can afford the costs of education ($C_{it} > F_s$), and value *0* if it cannot. If an agent cannot afford more education, it will have to devote all of its productive time to work ($v = 0; T_{it}^{(S)} = 0; T_{it}^{(W)} = T_{it}^{(P)}$). This means that an agent that exhausts its financial capital endowments will likely be locked in a trap: it will have to work full-time, and its skill and wage level will not develop over time (unless the agent will save part of its income, restore its financial endowment, and thus be able to finance again further education). On the other hand, richer individuals, given a greater endowment of financial capital, have more opportunities to educate, re-train and increase their skills and wage levels over time.

This formulation has an interesting implication: the model generates a U-shaped relationship of well-being over the life cycle, reproducing a well-known empirical stylized fact in the well-being literature (Blanchflower and Oswald, 2004). In fact, taking first differences of equation 1 with respect to time, it is easy to see that $\frac{\partial U_{it}}{\partial t}$ is concave. The lower panel of figure 1 shows this relationship. The reason for the U-shaped relationship in our model is that well-being decreases during the first part of life, when young individuals must invest time for skill formation, and then progressively increases in later years, when individuals work, earn an income and can afford greater consumption and leisure possibilities. Note also that figure 1 illustrates the overall patterns for an average agent. However, these patterns will differ among agents. For richer (poorer) individuals, the U-shape of well-being will initially decline more (less), and then increase sharply (slowly) during the course of working life.

Innovation and technology adoption. The model assumes that innovations are exogenously introduced in the economic system. The probability that an innovation is introduced at any given time t is given by parameter α:

$$Pr[INNO = 1] = \alpha \tag{19}$$

When a new innovation is available, agents will start to use it. Adoption of a new technology is endogenous. The probability that an agent will adopt the innovation at time t is defined by:

$$Pr[ADOPT_{it} = 1] = \beta \cdot S_{it} + \gamma \cdot N_{it}^{(A)} \tag{20}$$

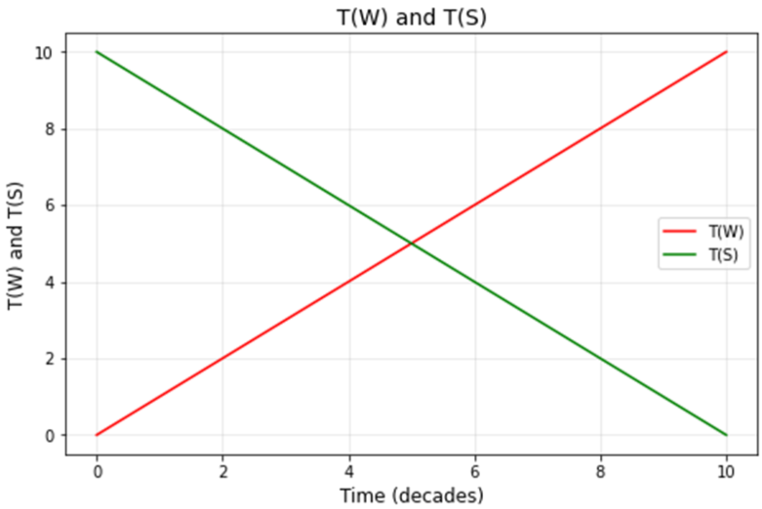
The probability of adoption depends on two factors: the first is the agent' skill level (S), and the second term is the number of neighbors of that agent that have previously adopted the innovation ($N^{(A)}$). In other words, the diffusion of new technologies in the economic system increases with individuals' skill level (that affects their ability to understand and use new innovations) as well as network effects related to peer effects in technology use (Kiiski and Pohjola, 2002; Zeppini and Frenken, 2018).[3]

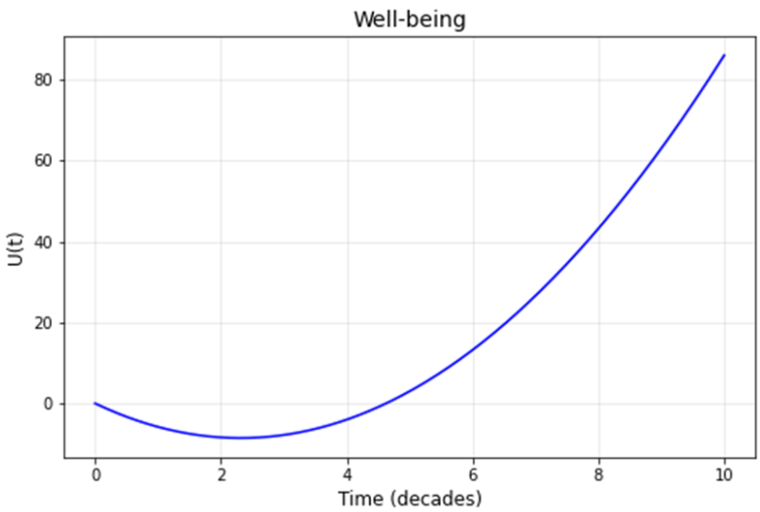
Once an agent adopts and starts to use a new technology, this will affect some of the relationships in the model, which will become stronger (or weaker) as a consequence of the fact that the agent is using the innovation. For instance, referring to equation 2, if a new product variety is available in the market, parameter b (effect of consumption on well-being) will be higher than it was before the new variety was introduced. A similar reasoning applies to several other parameters of the model (as I will elaborate in further details in section 4). To incorporate this idea into the model, I define a subset of parameters that represent relationships that may be affected by the introduction of innovations:

$$[\mathbf{P}_j] = [P_1; P_2; \ldots; P_q] \tag{21}$$

[3]Further, since the skill level S is a determinant of the probability of adoption, this formulation implies also that individuals with higher wage and income are more likely to adopt new technologies (given that wage is a function of the skill level; see equation 4).

Figure 1: Dynamics of time allocation and well-being for a given individual





Each term of the vector $[\mathbf{P}_j]$ represents a parameter of interest to analyze the effects of innovation. Each term P_j can be defined as:

$$P_j = P_j^{(NA)}; \text{ for } ADOPT_{it} = 0$$
$$P_j = P_j^{(NA)} + P_j^{(A)}; \text{ for } ADOPT_{it} = 1 \quad (22)$$

In other words, each parameter in this vector takes an initial (baseline) value ($P_j^{(NA)}$) for agents that have not adopted yet the innovation, and it increases by the term $P_j^{(A)}$ for agents that adopt the innovation. In the simulation analysis (section 4), I will simulate the effects of innovation on well-being by analyzing how changes in each parameter of interest affect the aggregate outcomes of the model.

3 Model dynamics

3.1 Empirical calibration

The model is empirically calibrated for the US. The US represents a relevant case for the topic investigated in this paper. In the last decades, this country has experienced rapid technological dynamics and steady economic growth, on the one hand, and stagnant well-being, on the other (see empirical evidence presented in table 1 above).

Calibration moments. I define first the calibration moments, i.e. the main macro stylized facts and outcome variables of interest that the model seeks to reproduce, considering the four-decade period 1980-2020. Regarding demographic aspects, the US has in these decades experienced an increasing population, and an overall stable mean age. Human capital has steadily grown (+50% total growth of tertiary enrolment ratio). The GDP per capita has also grown throughout the period (+6% per year in PPPs). As for technological innovation, its growth has been substantial (+300% growth in total patents granted at USPTO). On the other hand, indicators of well-being and life satisfaction, as reported in table 1 above, indicate a stagnant dynamic. For instance, the happiness level reported by individuals in several waves of the World Value Survey has only grown by a total 4% during this four-decade period. Finally, it is also important to note that income inequalities within the US have increased (+5% Gini index), a feature that our model will also seek to reproduce.

Shifting the focus to the model's parameters, these were calibrated by using empirically plausible values, based on empirical evidence and prior literature, and/or by setting values that lead to a good fit between simulated variables and the related moments. I briefly discuss them here, and table A.1 in the appendix reports the values of all parameters in the baseline version of the model.

Population dynamics. The model starts with a population of 1000 agents (individuals). To calibrate parameter o (probability to get sick), I use empirical data on the prevalence of chronic conditions in the US (defined as the percentage of individuals experiencing ongoing health issues). These indicate that, in the US in 1980, approximately 34% of U.S. adults aged 18 and over reported having one or more chronic conditions (source: Centers for Disease Control and Prevention). I have therefore set parameter o to 0,34. Parameter p represents the mortality rate, which was 0,88% in the US in 1980 (source: National Centre for Health Statistics). Parameter q is the general fertility rate (GFR: probability of birth in a given year). In 1980, the GFR in the U.S. was 68,4 births per 1000 women aged 15–44 (source: National Vital Statistics Reports). Hence, I set q to 6,8%.

Skills and wages. Parameter h denotes the effects of education investments on the individuals' skill level. Micro- and macro-level estimates of the relations between time invested in education and educational outcomes (or skills) range between 0,3 and 0,6 (Lavy, 2015; Hanushek and Woessmann, 2008). However, the parameter is arguably lower in countries that have already an advanced level of human capital and therefore lower marginal returns to education. Hence, I set h to 0,10, a somewhat lower value that represents better the more advanced human capital level in the US in the 1980s. Parameter g is the elasticity of wage with respect to the skill level. Card (1999) reports IV estimates of the returns to schooling at around 8–12% per year of schooling. Meta-regression analyses of the Mincer equation literature indicate 8% return per year of schooling (Psacharopoulos and Patrinos, 2004). I set g to 10%.

Utility function. Parameter a measures the relative importance of work and leisure for well-being. The well-being literature points out that, although this parameter varies somewhat across socio-economic groups (Dolan et al., 2008), it is reasonable to set it to an average value of 50%. Regarding parameter b, it assumes constant utility per unit of consumption. This is a reasonable assumption in a long-term framework, in which the consumption basket evolves dynamically with the introduction of new goods and services that satisfy new preferences over time. I set it to a high level (0,95), because this parameter only reflects the absolute income effect, i.e. the effects of consumption (including new varieties) on material well-being (disregarding relative income and adaptation effects that are considered separately). As for parameter c (relative income effects), according to the well-being literature, it is reasonable to set a value between 0,4 and 0,5 in the context of advanced economies (Clark, Frijters, and Shields, 2008; Layard et al., 2008; Ferrer-i-Carbonell, 2005). Parameter d represents adaptation effects. Estimates for advanced economies indicate that adaptation effects may reduce well-being up to 40% for an average individual (Ferrer-i-Carbonell and Van Praag, 2008; Di Tella et al., 2010). I therefore set a value of d to 0,40 in the baseline model. The saving propensity is set to 8%. This is in line with figures for the US, that report a saving propensity between 7 and 10% in the 1980s and 1990s (source: US Bureau of Economic Analysis).

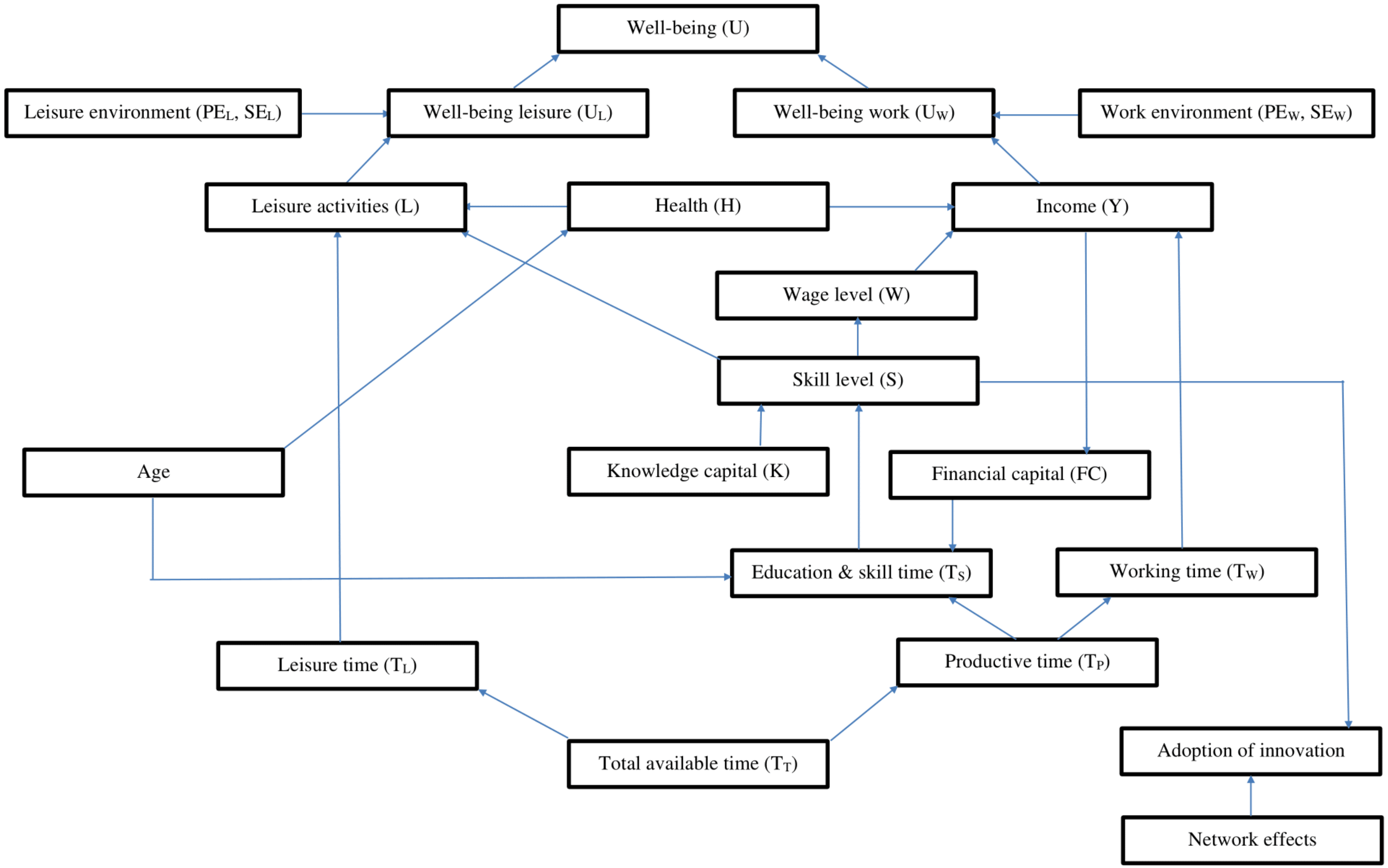
Time allocation. There are no exact historical figures to calibrate these parameters. Statistics for recent years indicate that the share of daily working hours *versus* leisure hours for an average person in the US is 60% versus 40% (source: American Time Use Survey, U.S. Bureau of Labor Statistics). However, it is reasonable to assume that the share of working time was lower in earlier decades. Hence, I set these shares to 70% and 30%, respectively.

Technological innovation. Parameter α is the probability that an innovation is found at any time t. I set this parameter to 3,5%, as this corresponds to saying that on average there will be approximately a 300% total growth of innovations (i.e. new patents) after 40 years, which corresponds to the real trend that is observed in USPTO data (see table 1).

3.2 Model's implementation and outcomes

I have implemented the ABM model in *Netlogo* 6.0.3. Figure 2 shows an overview of the main variables of the model, and the sequence of steps that each agent performs at any time t.

Figure 2: ABM model: Main variables and sequence of steps at each time t for each agent



To provide an understanding of the functioning of the model, this section presents its dynamics and the time paths of the main variables of interest. Figure 3 shows the time paths of the main variables of the model for a period of 150 years. I have carried out 100 Monte Carlo repetitions of the baseline simulation, and the points depicted in the plots in figure 3 are average values of these repetitions. The time path of the population variable, which is driven by the joint effect of mortality and fertility rates, show that the total number of agents increases over time, in line with empirical evidence for the US. The population's mean age (not reported in figure 3) is stable over time (around 30 years). The plot reporting the patterns of technology adoption shows that the adoption rate (share of the population that uses a given innovation at time t) increases rapidly in the early phase of the model run – as soon as an innovation is introduced in the economic system – and it then maintains a stable and high level during the rest of the simulation run.[4]

Regarding financial capital (graph not reported in figure 3), the mean capital endowment increases over time, since at any time t agents save the part of their income that is not devoted to consumption. Hence, on average, the economy accumulates financial capital over time. However, the distribution of financial capital among agents of the population is unequal. The share of financial capital owned by richer agents increases rapidly *vis-à-vis* the share owned by less affluent individuals.

Individuals allocate their time between work, education and skill formation, and leisure. On average, time allocation tends to a stable level in the model (working time: 60%; education and skill formation time: 10% leisure time: 30%), that is in line with the empirical evidence for the US noted in sec. 3.1. Since individuals spend a fraction of their time to improve their education and skills, the average skill level in the population increases steadily over time. The simulated pattern is consistent with the steady growth of tertiary enrolment ratios in the US in the last four decades. Correspondingly, the mean wage level (not reported in figure 3) does also increase steadily over time. However, the dynamics of average skill and wage levels is driven by unequal patterns for different groups of the population. Agents that have higher endowments of financial capital can afford to pay the costs of education and training during their entire lifetime, thus increasing their skill and wage levels over time. By contrast, less affluent individuals do not have sufficient financial capital (or they will exhaust it at some point during lifetime), and they will thus be unable to invest further time in education and training. The latter group will therefore experience stable and stagnating skill and wage levels over time.

The lower half of figure 3 reports plots for the time paths of the two main outcome variables of the model: income (Y) and well-being (U). Mean income grows steadily over time (driven by the dynamics of skills and wages). This is also a key feature of the US economy in the last four decades. Leisure activities (L; not reported in figure 3) do also increase on average over time, due to the fact that the model assumes that an increase in skills will not only provide better opportunities in working life, but it will also imply a greater ability of individuals to choose rewarding leisure activities, thus fostering well-being from leisure.

The dynamics of income is one of the main factors driving the dynamics of well-being. Figure 3 shows that average well-being increases over time, although its rate of growth

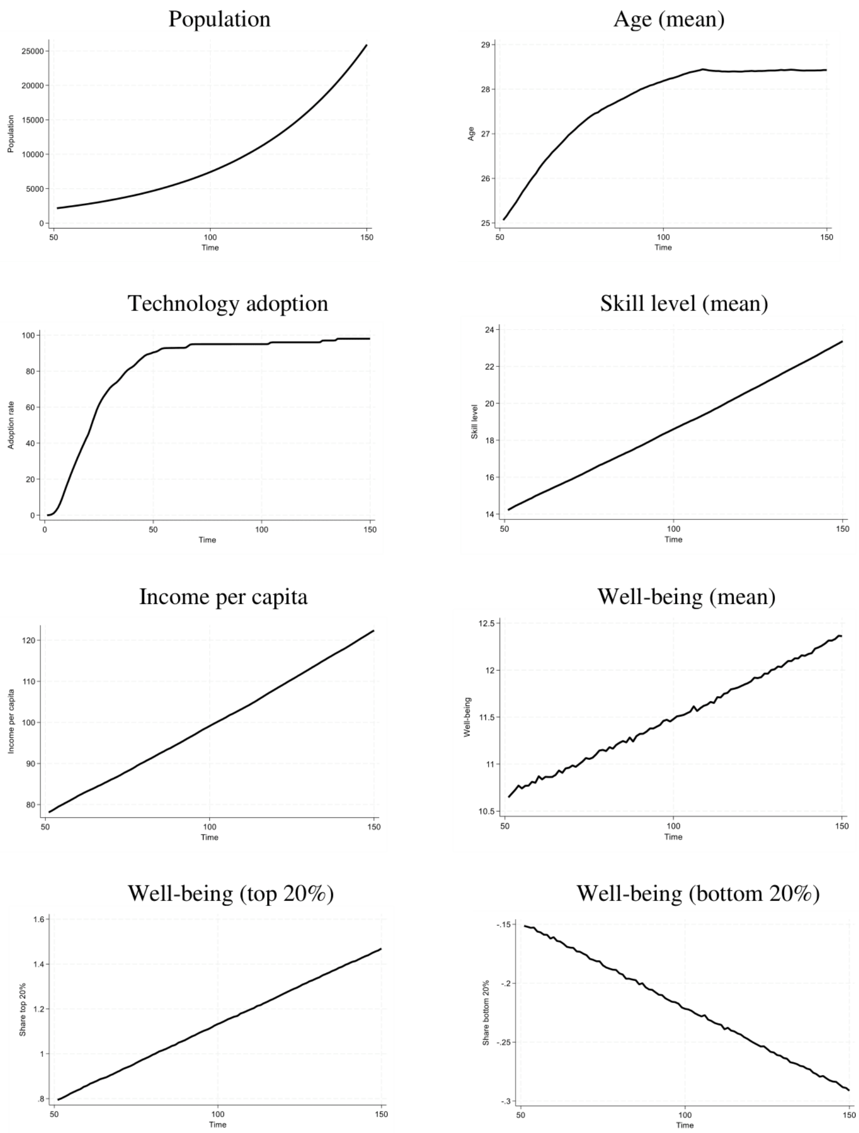
[4] For simplicity, the model assumes that once an innovation is introduced in the economic system, this will continue to dominate the technology landscape in the long-run. In other words, we do not consider the case of competition between different technologies, and/or the decline of obsolete technological paradigms over time.

is much lower than that of mean income. The reason why average well-being does not grow as rapidly as mean income is that relative income effects and adaptation effects (see equation 2) partly offset the growth of well-being that is due to absolute income effects (that foster utility via consumption and preference satisfaction). This outcome of the model, according to which well-being dynamics is much slower than income per capita growth, is in line with the well-known *Easterlin paradox* (Easterlin, 1995).

Finally, the two plots at the bottom of figure 3 show the dispersion of well-being, measured by the average utility of the richest 20% and the poorest 20% of the population, respectively. The graphs indicate that well-being is increasingly concentrated over time, and less equally distributed among agents in the population. The mean utility level of the 20% richest increases over time, whereas that of the 20% poorest decreases. The reason, in line with what noted above, is that the model has a built-in mechanism that leads to greater polarization between rich and poor agents. On the one hand, agents that have a higher initial endowment of financial capital (due to family background, or random factors) can invest in education and skill formation during lifetime, thus increasing their skill and wage levels, as well as their income, consumption and well-being. On the other hand, the decline in U for the poorest 20% is driven by these mechanisms: (1) relative income effects may lead to decreasing U when average Y increases more rapidly than Y of the group of poorest individuals; (2) lack of capital to invest in education will reinforce this effect; (3) late adoption of technology, due to lower skill levels, will also reinforce this pattern.

In the remainder of this paper, I will mainly focus on the effects of innovation on average well-being (*efficiency effects*), which is the central topic of this paper, and not focus on the corresponding impacts of innovation on the distribution of well-being (*equity effects*). However, the latter type of impacts is important too, because in this model distributional changes may turn out to affect average well-being through relative income effects. As shown in the next section, innovation plays a key role in this respect.

Figure 3: Time paths of the main variables of the model (150 years, average of 100 Monte Carlo repetitions)



4 The seven effects of innovation on well-being

This section will point out and discuss seven distinct effects that link innovation and well-being. Our argument is that – although innovation is a broad phenomenon that encompasses several different types of technological and organizational changes – all different innovations that we may think of affect well-being through one or more of the effects noted in this section. To illustrate each of the seven effects, I carry out a set of simulation analyses of the ABM model. Specifically, as explained at the end of section 2, each effect of interest is associated with one or more parameters of the model (vector $[P_j]$, see equation 21). For each parameter of interest, the simulation analysis has assigned 100 different values in the parameter's range. More precisely, I have assigned 100 different values to each parameter of interest for agents that are adopters of innovation (see term $P_j^{(A)}$ in equation 22 above), meaning that a given effect of innovation becomes progressively stronger over time in the population as that innovation is gradually adopted by more and more agents. Assigning different values to each parameter in the simulation analysis represents the idea that the effects of different innovations may have different magnitude and strength, and the simulation analysis seeks to identify the impacts of these on aggregate well-being.

For each simulation, I have and run the model for 1000 periods and computed the final value at $t = 1000$ of the three main outcome variables: average well-being (U), average work well-being (U^W) and average leisure well-being (U^L). Each simulation has been run for 10 Monte Carlo replications. The results of this simulation analysis are summarized in a series of plots in figure 4, where each plot reports the population's well-being at $t = 1000$ (y-axis) against different values of the parameter of interest (x-axis).[5]

4.1 Wage-related effects

1A. Innovation profits and wage dynamics. A key tenet in the economics of innovation is that when new technologies are developed and commercialized by companies, the sales of these new products and services lead to an increase of profits and market shares for innovative firms. In turn, the rents of innovation translate into higher wages for some workers in these companies (managers, R&D personnel, high-skilled workers). Workers that benefit from technological change increase their wage *vis-à-vis* other workers that do not benefit from innovation to the same extent (e.g. low-skilled and routine-task workers). Hence, the process of creative destruction induced by innovation is often associated with increasing wage polarization (Aghion et al., 2019; Acemoglu and Restrepo, 2020; Hemous and Olsen, 2022). In our model, this mechanism is represented by parameter g, which measures the effects of innovation on wage (i.e. representing the "skill-premium"). Figure 4.1 shows that increasing values of this parameter (that simulate increasing degrees of skilled-bias technological change in the economy) lead to higher average well-being in the population. As noted in section 3, though, this increase in aggregate well-being is also associated in this model with a greater degree of wage polarization between skilled and less skilled workers, and therefore an increasing dispersion of income and well-being among different groups of agents in the population.

[5] I have also recorded outcomes in terms of inequality of well-being (measured as the average utility of the richest 20% and the poorest 20% of the population, as noted in section 3). I will not report in details results on inequality patterns (since this is not the main focus of the present paper), but I will briefly summarize these in the text when they provide relevant information to understand the effects of innovation.

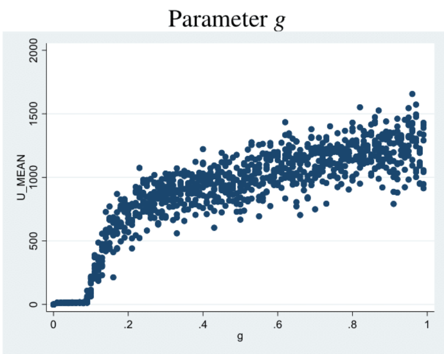
1B. Relative income. An important point that is neglected in the economics of innovation, though, is that changes in the profit and wage distribution that affect the relative economic position of agents *vis-à-vis* others also have potentially important consequences for subjective well-being. In fact, happiness studies point out that a relative income effect (see section 2, equation 2) is always at work when agents consume new goods and services, because individuals compare their consumption patterns and economic possibilities to those of their peers (Senik, 2005; Clark and Senik, 2010). This effect will magnify the impacts of the process of creative destruction and wage polarization: it will further increase subjective well-being for those individuals that experience higher wages and relative income, and it will further decrease well-being for those agents that face a decrease in economic opportunities *vis-à-vis* their peers.

Furthermore, some recent innovations make individuals more prone to social comparisons, such as social media and Internet services that expose individuals to images of affluence (Lohmann, 2015; Sabatini and Sarracino, 2017). These digital platforms increase the importance of relative income comparisons for subjective well-being, and decrease the utility that individuals derive from a given level of income and consumption. In the ABM model, the relative income effect is represented by parameter c. The corresponding plot in figure 4.1 shows that higher values of this parameter (that simulate the effects of innovations that make agents more prone to compare their economic opportunities to those of their peers) are associated with lower levels of average well-being in the population. This negative relationship is explained by the fact that the model leads to increasing disparities between rich individuals and a larger group of poor agents, so that, on aggregate, a stronger relative income effect will generate a larger amount of discontent for less affluent individuals than the corresponding increase in well-being for the richer groups of the population.

Considering together the two effects noted above (1A and 1B), the net impact of this type of mechanism on well-being may be complex. On the one hand, innovation profits and wage growth have a positive impact on the economic well-being of the affected individuals. On the other hand, however, skilled-bias technological innovations will increase income inequalities, which will also lead to increasing disparities in well-being via relative income effects. Hence, the net impact on the average well-being of the population is uncertain, since relative income effects attenuate and partly offset the positive impact of skilled-bias technological change and creative destruction on aggregate well-being. To illustrate this point, I have carried out another simulation analysis that simultaneously increases the value of both the g and c parameters. Table 2 reports results of OLS regressions of joint variations of the two parameters on the average well-being of the population. The regression results indicate that, for the parametrization used in the baseline model, the overall effect is negative, i.e. the negative impact of relative income comparisons on average well-being is so strong as to overturn the positive impact of innovations via profits and wages.

Figure 4.1: Wage-related effects

A. Innovation profits and wage dynamics.



B. Relative income effect.

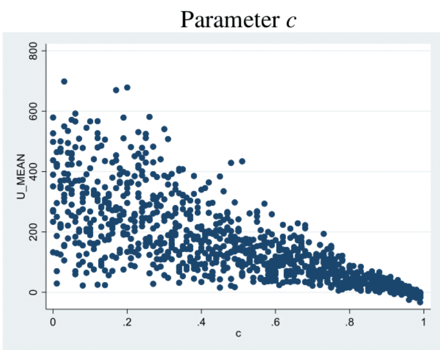


Table 2: Wage-related effects: Effects of joint changes in g and c: OLS results on simulated data (3K design)

	Coefficient	(Standard Error)
g	9627.66	$(140.5)^{***}$
c	1407.41	$(20.25)^{***}$
$g \cdot c$	-18509.57	$(159.08)^{***}$
Adjusted R^2	0.987	
Observations	900	

4.2 Consumption-related effects

This is the well-known transmission mechanism that is at the core of endogenous growth theory. The creation and commercialization of new products and new services enlarge the range of available consumption opportunities. Since agents like to consume new items ("love for variety"), the consumption of innovations will lead to the satisfaction of new preferences and so increase agents' utility and material well-being (Trajtenberg, 1989; Aghion and Howitt, 1998). Although mainstream economics theory focuses on the positive effect that innovations have on well-being through consumption, I argue here that there are two distinct consumption-related effects of innovation on well-being, and that may turn out to be in contrast with each other.

2A. Increased consumption. This is the standard and well-known effect. When agents have a higher absolute income, they can consume more and thereby increase their utility via preference satisfaction. In the ABM model, two parameters represent this idea. One is parameter b, which measures the effects of consumption on well-being. The other is parameter ϵ, which is the saving propensity (such that $(1-\epsilon)$ is the consumption propensity). The introduction of new products and services in the market fosters well-being because these innovations will lead to the satisfaction of new preferences (parameter b) as well as increase agents' propensity to consume these new items $(1-\epsilon)$. In figure 4.2, the two plots in the upper part of the figure show the results of simulation analysis of these two parameters. The plots illustrate that average well-being in the population increases for increasing values of b and for higher values of the consumption propensity, respectively.[6]

2B. Adaptation. An important mechanism that is neglected in the economics of innovation – but extensively investigated in well-being studies – refers to adaptation effects. As noted in the ABM model (see section 2, equation 2), well-being derived from absolute income and consumption is partly offset by agent's income and consumption level in the previous period, representing the idea that agents tend to be better off (worse off) when their consumption increases (decreases) compared to the previous period (Shafir, 2016). I argue that this mechanism is particularly relevant to study the effects of innovation on well-being. In fact, there are several examples of innovations (e.g. digital innovations; e-commerce) that tend to make consumers more impatient, increasing their pace of adaptation to a given consumption level. This idea is represented by parameter d in the model. In the simulations, increasing values of d simulate the effects of innovations that make individuals more impatient, thus increasing the average pace of adaptation in the population. As shown in figure 4.2, higher values of this parameter are associated with lower levels of well-being in the population, since adaptation mechanisms attenuate and partly offset the positive effects of increased consumption on well-being (i.e. point 2A above).

Overall, considering together mechanisms 2A and 2B, the net effect of innovation on well-being via consumption depends on the complex combination of the two contrasting mechanisms – increased consumption *versus* adaptation. This net effect is complex and highly uncertain, and it is not necessarily positive as typically assumed in a mainstream framework. To highlight this point, I have carried out another simulation analysis that simultaneously increases the value of both the b and d parameters. Table 3 reports

[6] The graph for the consumption propensity also shows that when parameter $(1-\epsilon)$ is very high the average well-being of the population decreases. The reason for this is that if individuals consume most of their income and do not save, they are not able to keep financial capital that is necessary to finance the education costs, which agents incur when they seek to increase their skill and wage level over time.

results of regressions of joint variations of the two parameters on the average well-being of the population. The interaction term is not statistically significant for the specific parametrization used in the baseline model, indicating that it is indeed hard to identify *ex-ante* the overall net impact of innovation on average well-being via consumption-related effects.

Figure 4.2: Consumption-related effects

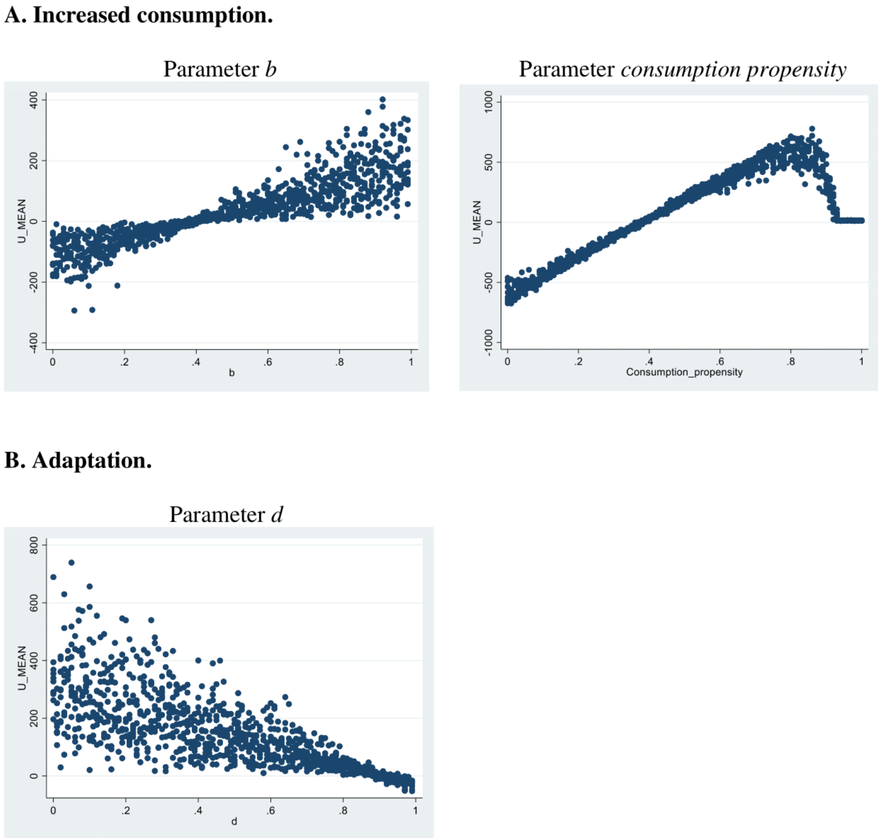


Table 3: Consumption-related effects: Effects of joint changes in b and d: OLS results on simulated data (3K design)

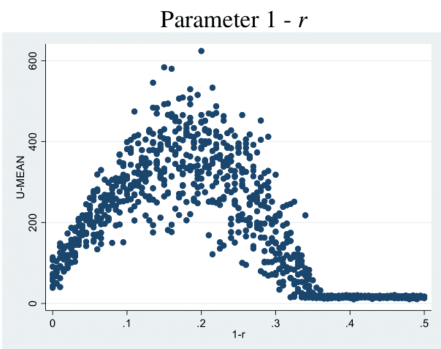
	Coefficient	(Standard Error)
b	421.25	(2.87)**
d	-1141.85	(7.21)***
$b \cdot d$	24.71	(0.10)
Adjusted R^2	0.264	
Observations	810	

4.3 Time use effects

One major effect of innovation on well-being is that it affects the way in which individuals use their time and allocate it to different activities. In particular, there are plenty of examples of innovations that increase labor productivity and lead to time-saving effects at work, thus making it possible to reduce the time that individuals have to devote to work, and correspondingly increase leisure time that leads to further well-being (Martin, 2016; Castellacci and Tveito, 2018). In the model, parameter r measures the share of time that agents (on average) allocate to productive *versus* leisure activities. Decreasing values of parameter r (and hence increasing values of $1 - r$) simulate the effects of technological changes that, in the long-run, have progressively reduced the average number of working hours and freed up time for leisure. In this ABM, parameter r has three related and contrasting effects on well-being. First, innovations enabling time-saving at work and more leisure time (lower r) will lead to higher well-being from social life and leisure. Second, at a given time t, for a given wage level, a reduction in working time implies lower income, consumption and well-being. Third, if higher leisure time reduces also time devoted to education and skill formation, the reallocation of time from work to leisure will slow down skill and wages dynamics, and hence utility from income in future periods. Figure 4.3 shows that the combined effect of these three mechanisms is concave. Up to a certain threshold, lower values of r are associated with higher average well-being (due to the prevailing effect of the first mechanism noted above); after that threshold level, lower values of r are associated with lower average well-being (i.e. the second and third mechanisms noted above prevail for the range of r after the threshold). Hence, the simulation points out an optimal level of r that balances the three contrasting effects.

It is also important to note that – in addition to reducing working time due to time-saving effects – some innovations may also affect the way in which individuals use their time. For instance, some digital technologies (e-mail; mobile phones; video meetings) are currently blurring the boundaries between work and leisure time, and they often end up increasing working time *vis-à-vis* leisure time (Castellacci and Bardolet, 2019). To take this effect into account, we would interpret the plot in figure 4.3 as follows: increasing values of parameter r represent technological or organizational changes that lead to increasingly blurring boundaries between work and leisure, and consequently higher work pressure and working time for the individuals. Again, the effects of this type of change on well-being would be non-linear, for the same reasons noted above.

Figure 4.3: Time use effects



4.4 Social communication effects

Innovation affects the way in which individuals communicate with each other. Two related mechanisms are relevant here.

4A. Distant communication. Innovation affects people's well-being because it provides new opportunities for remote communication. The telegraph, the telephone and, more recently, digital services that enable distant online communication are all important examples of innovations that have provided individuals with new opportunities for communication and social interactions for agents that are not co-located (Antonelli, 1998; Nelson, 2011). Greater opportunities for social interactions enlarge an individual' social network, thus potentially fostering well-being from leisure activities. A simple way to analyze this transmission mechanism in this ABM model is to simulate the effects of changes in parameter n. This parameter measures the effects of social interactions on well-being (for a given level of the quality of social interactions $SE^{(L)}$; see equation 6). Increasing values of n simulate the effects of new technologies that foster well-being by creating new opportunities for remote communication among agents. Figure 4.4 shows simulation results indicating a positive relationship between parameter n and average well-being from leisure.

4B. Quality of social interactions. While innovations create more opportunities for remote communication and social interactions at distance, thus enlarging the extent and reach of individuals' social networks, these same technologies may also affect the quality of the socio-institutional environment in which agents carry out their work and leisure activities. These effects can be either positive or negative, depending on the specific innovations at stake. For instance, the quality of social interactions may be negatively affected if agents use social media services and other digital technologies as substitutes, rather than complement, to face-to-face interactions in their social life. This is a topic that is currently being investigated in the fields of psychology and computer-human interactions (see e.g. Kraut et al., 1998; Oh et al., 2014; Castellacci and Tveito, 2018). Similarly, it is well-known that the use of digital technologies that enable telework (e.g. video meetings) may threaten the quality of social interactions at the workplace (Golden and Veiga, 2005). In the ABM model, the two parameters $SE^{(W)}$ and $SE^{(L)}$ represent the quality of social environment at work and for leisure, respectively. Variations of these parameters may be used to simulate the effects of changes in the quality of the socio-institutional environment on well-being. Simulated data in figure 4.4 point out a positive relationship between parameters $SE^{(W)}$ and $SE^{(L)}$, on the one hand, and average well-being from work and leisure, on the other. This relationship is general, and it is meant to represent different types of communication technologies. If these new technologies or new work arrangements increase the quality of social interactions, they will lead to a higher average level of well-being of the population; by contrast, if they decrease the quality of social interactions, they will reduce well-being.

Considering together the two effects (4A and 4B), they are complementary with each other, in the sense that a new technology that enables better distant communication, while also increasing the quality of social interactions, will have positive impacts on the average well-being of the population. To illustrate this further, I have carried out a simulation analysis that simultaneously increases the value of both the n and $SE^{(L)}$ parameters. Table 4 reports results of OLS regressions of joint variations of the two parameters on average well-being, indicating a positive and statistically significant interaction effect.[7]

[7]Using the same logic discussed here, it would also be possible to study the effects of an innovation

Figure 4.4: Social communication effects

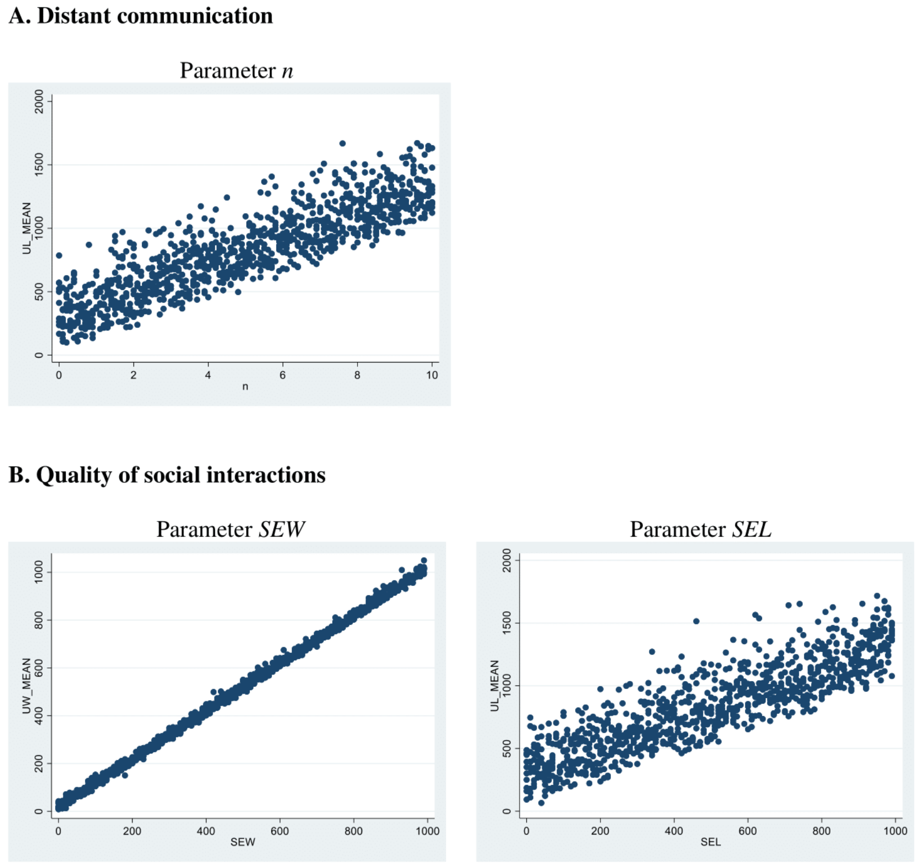


Table 4: Social communication: Effects of joint changes in n and $SE^{(L)}$: OLS results on simulated data (3K design)

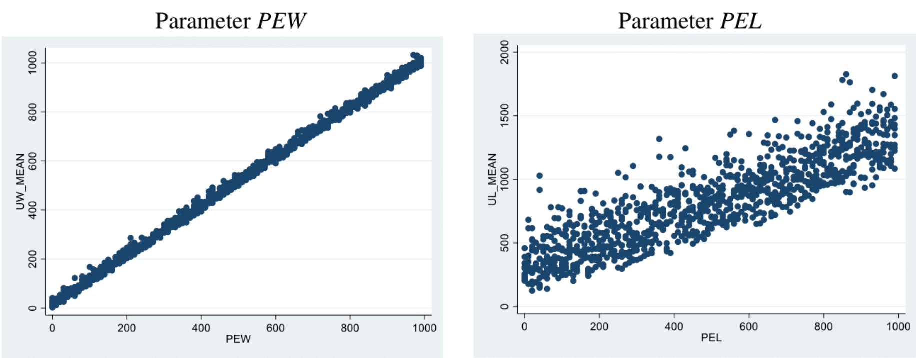
	Coefficient	(Standard Error)
n	400.08	$(49.27)^{**}$
$SE^{(L)}$	8594.28	(1.05)
$n \cdot SE^{(L)}$	35073.85	$(25.28)^{***}$
Adjusted R^2	0.829	
Observations	900	

that has, say, positive impacts by enabling distant communication, but negative effects by decreasing the quality of social interactions (e.g. telework; social media). In this case, the net effect of the two opposite mechanisms on well-being would be hard to predict *ex ante*, and it would depend on the specific parametrization used in the model, or the data and indicators used in an empirical analysis of this topic.

4.5 Physical environment effects

In well-being studies, individuals' quality of life is not only shaped by the activities they carry out in different domains of life, but also by the quality of the environment that characterize the place and location where they live. Technological innovations do contribute to transform the physical environment in a variety of ways. Important illustrations are green innovations that reduce pollution and/or use renewable sources of energy, contributing to create a better and more sustainable environment that enhances the well-being of the present and future generations (Witt, 2021). On the other hand, there are also examples of new technologies and production processes that pose environmental risks due to an intensive use of dangerous chemicals, rare minerals or non-clean energy sources (Biggi and Giuliani, 2020). We may also think of the physical environment in a more narrow and more specific way, i.e. the physical work environment where individuals carry out their work activities. A relevant example here relates to automation technologies, which often reduce risky conditions and monotonous tasks for factory workers, thus fostering this dimension of well-being in working life (Castellacci and Bardolet, 2019). The two parameters $PE^{(W)}$ and $PE^{(L)}$ represent in this model the quality of physical environment at work and for leisure activities, respectively. Figure 4.5 shows a positive relationship between each of these two parameters and well-being from work and leisure, respectively. This positive relationship means that innovations that improve the quality of the physical environment lead to higher aggregate well-being, whereas those that pose threats and risks to the quality of the physical environment lower population's well-being.

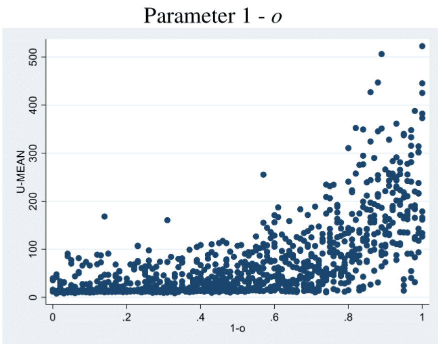
Figure 4.5: Physical environment effects



4.6 Health effects

Innovations that have an impact on individuals' health are fundamental for well-being. Medical and pharmaceutical innovations that improve health have in fact an important double effect on well-being. First, by addressing a given medical condition, they contribute to reduce pain and suffering for an agent and its relative others, thus fostering subjective well-being (Deaton, 2008). Second, if an individual is sick, she does not have the possibility to work and participate actively to social life and leisure activities. Health innovations, by improving agents' health, do therefore increase the range of functioning that individuals can have and make use of in their in working and social life, thus opening up a broad range of opportunities to well-being (Graham and Nikolova, 2015). By contrast, we may also think of instances in which new technologies have negative, though unintended, effects on individuals' health and well-being, such as the use of dangerous chemicals and pesticides (Biggi and Giuliani, 2020), or robots affecting mental health of workers (Schwabe and Castellacci, 2020). In this model, this type of effect is represented by parameter o, which denotes the average probability to get sick (for any given age). As noted in section 2, this is a population-level parameter that reflects the status of science and technology in medical fields and the country's health sector. In the simulation analysis, lower values of parameter o correspond to a lower number of sick agents in the population, and a higher average well-being. The positive relationship between health innovation and well-being is illustrated by the plot in figure 4.6.

Figure 4.6: Health effects



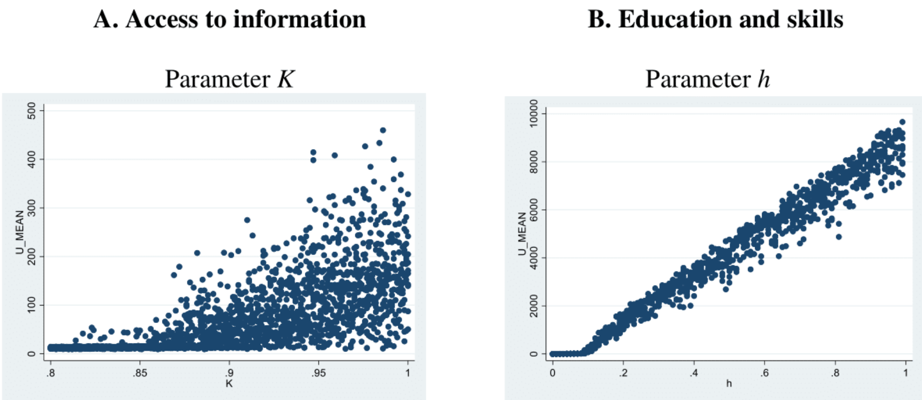
4.7 Value-shaping effects

By value-shaping effects, I mean that innovations may affect the way in which individuals value their life circumstances, set up priorities and preferences, and carry out their choices. Specifically, innovations may shape individuals' values in two related manners.

7A. Access to information. The first is through availability and access to data and information. Throughout the history of humankind, different innovations have enabled the codification, storage and sharing of data and knowledge (Antonelli, 1998). This has had terrific effects for agents' well-being. The increased amount of knowledge that is publicly available, or that can be accessed at lower costs than earlier, has three important effects: it fosters productivity and wage at work; it improves the quality of education and training activities; and it does also enable individuals to carry out better informed choices, both in consumption and leisure activities (Castellacci and Tveito, 2018). In the ABM model, parameter K represents the stock of publicly available knowledge that agents can use for productive and leisure activities. Increasing values of this parameter simulate the introduction of innovations that enable a greater codification, storage and sharing of data and knowledge (e.g. Internet technologies). The plot in figure 4.7 (left panel) reports the results of this simulation analysis. Higher values of K lead to a strong and rapid increase of average well-being. This effect is so strong because in this model knowledge capital fosters skill dynamics, which in turn leads to both higher well-being at work (via wage and income dynamics), and higher leisure well-being (since greater skills also increase agents' ability to choose leisure activities that are more conducive to well-being).[8]

7B. Education and skills. When technological or organizational innovations are implemented in the education sector, these foster the quality of the education and training system, and lead to greater opportunities to transform publicly available knowledge into new agents' skills (Nelson, 2011). In turn, skill dynamics foster well-being in two ways: it strengthens opportunities and wages at work; and it enables individuals to carry out better informed choices about their leisure activities. In the ABM, the relevant parameter to consider this mechanism is h, which measures how easy it is for an agent to increase its skills over time. Higher values of h simulate innovations that improve the quality of the educational system, thus making it easier for individuals to increase its skills over time (for any given amount of time that the agent invests in education and skill formation). Figure 4.7 (right panel) reports the results of the simulation analysis for this parameter, showing a sharp positive effect of educational innovations on average well-being. In summary, access to information and educational innovations are particularly important in this conceptual framework, because they have a complementary positive impact on well-being. They do not only improve subjective well-being directly by improving skills; but they also increase agents' capabilities and functioning that are necessary to carry out activities in all other domains of life.

Figure 4.7: Value-shaping effects



[8]It is worth to make two clarifications. First, it may be argued that when parameter K is very large there may be *knowledge congestion effects*, i.e. individuals may find it hard to screen a large pool of available knowledge, and the implications of this situation for individual well-being would not be clear. However, the model implicitly takes this into account because higher values of K increase well-being at work through wage and income dynamics, which are in turn subject to decreasing returns (due to relative income and adaptation effects). Second, for simplicity, the argument presented here assumes that publicly available knowledge is good for well-being. It would of course be possible to think that some types of publicly available knowledge – such as *fake news*, for instance – would not be good for individual well-being. However, this would not affect the overall logic of this mechanism. In this case, increases in the amount of publicly available "bad" knowledge would *decrease* the average well-being of the population.

5 Discussion and challenges for future research

Key point. The key general point that the model seeks to show is that the various effects of innovation on well-being noted in the previous section have different relevance and different types of impact. First, some of the effects have transitory impacts, whereas others have lasting or permanent consequences. Specifically, consumption-related effects of innovation often affect well-being in a transitory manner, since the initial increase in well-being driven by the consumption of new varieties is partly reabsorbed and offset over time by adaptation and habituation mechanisms (section 4, point 2). By contrast, other effects of innovation have impacts on well-being that are more lasting in nature, such as innovations that change the way in which individuals use and allocate their time, communicate with other agents, and interact with the physical environment (section 4, points 3, 4 and 5).

Further, some of the effects pointed out in the ABM model inherently affect the distribution of income and well-being, fostering inequalities. In particular, for wage-related effects (section 4, point 1), the direction of impact for a given individual depends on its relative position in the wage or income distribution. On aggregate, relative income mechanisms magnify the impacts of innovation on well-being, thus fostering inequalities between winners and losers of the process of creative destruction.

Finally, innovations that foster individuals' health, access to information, education and ability to make independent value judgement are indeed crucial for well-being because they sustain individuals' capabilities and provide agents with opportunities to carry out a variety of functioning in all domains of life (section 4, points 6 and 7).

The bottom line of this argument is that innovations have multifaceted and diverse effects on well-being. Many innovations are crucial to promote human capabilities and well-being, whereas others foster consumption patterns that do not lead to long-run impacts of individuals' well-being. This is an important point for innovation research and for policy-making, because it suggests that – instead of supporting R&D and innovation activity in general terms – it would be more reasonable to provide public support, first and foremost, to those types of innovations that lead to capability building and permanent increases in well-being, and do not provide public support (and even discourage and regulate) to other types of technological changes that have only transitory, and sometimes negative, impacts on well-being.

What does this argument tell us about the empirical puzzle that was noted at the very beginning of this paper (see table 1)? Arguably, the fact that technological innovations (measured by patents) grew exponentially in the last four decades in the US, while average well-being of the population has been stagnant, may be due to the fact that many innovations that were developed and commercialized fostered consumption dynamics and the growth of GDP per capita, but these positive economic impacts contributed only marginally to the growth of average well-being of the population because of relative income effects, adaptation mechanisms and/or other non-economic negative effects among those discussed in the previous section.[9]

[9] A caveat is that our model has analyzed the various effects of innovation one by one. This has been a convenient way to present them clearly by using simulation analysis of different parameters of the ABM model. However, many innovations affect well-being through a multiplicity of mechanisms at the same time, and this makes it much harder to say if a given innovation has a positive or negative effect on the well-being of a given individual. To illustrate this point, let us take a couple of examples. First, the use of e-commerce provides terrific new opportunities for consumers, since these may make better informed choices and save substantial time. However, purchasing online may also solicit adaptation effects, if

Challenges for future research. An important implication is that, since innovations have multifaceted and diverse effects on well-being, it is important that research in this field will point out and discuss the impacts related to different innovation trajectories and distinct types of innovation, instead of assuming that technological and organizational changes will always lead to greater individual well-being and social welfare. Innovation research should in the future develop a typology to classify different types of innovations depending on the extent to which and the channels through which they affect individuals' well-being. This typological effort has also important normative implications, because it will provide policy-makers with a better grounded understanding of the types of innovations that are more important for well-being, and that should be promoted and supported. This task for future research is paramount, but it will face important methodological challenges, that I briefly discuss as follows.

1. A broad notion of well-being. Innovations may have impact on different dimensions of individual well-being: subjective (hedonic, evaluative) and objective well-being. Sometimes the same innovation affects multiple aspects of well-being for the same individual. It is therefore important that future research on this theme will adopt a broad notion of well-being rather than focusing only on material and hedonic well-being as it is often the case. This calls for interdisciplinary approaches and the cross-fertilization of insights on this theme of research between economics of innovation, on the one hand, and well-being studies, on the other.

2. Economic and non-economic effects. The effects of many innovations on well-being are at the same time economic and non-economic. In innovation studies, economic impacts (through wage, income and consumption dynamics) are typically pointed out as the major channels through which innovation affects welfare. However, some of the mechanisms that the model has pointed out are by their own nature non-economic, because they directly impact individuals by affecting their personal dimension (values, capabilities), extent and quality of social life, and/or quality of the physical and social environment. Non-economic impacts of innovation on well-being are hard to study and measure by means of monetary metrics only. The development of concepts, metrics and indicators to assess economic and non-economic impacts of innovation in the same framework is an important task for future research.

3. Direction of impacts. The model has pointed out that some of the effects have a clearly positive impact on well-being, whereas others have negative impacts. The few examples noted earlier in this section show that many innovations can have both positive and negative effects on an agent's well-being. In most cases, it is hard to say, *ex-ante*, whether the positive effects are stronger or more important than the risks and negative impacts that a given new technology entails for the individual. A joint assessment of the

online shopping leads to faster habituation and a less exciting and rewarding experience than physical shopping. A second example refers to telework (remote work enabled by the use of digital technologies). This is an important techno-organizational change that has been increasingly used in recent years. It has two contrasting effects on well-being. One is that it enables substantial time-saving for workers, thus increasing the time that these may devote to family and leisure *vis-à-vis* working and commuting time. The other, though, is that telework may also negatively affect the work environment and social capital at work, because digital interactions do not provide the same opportunities and quality as face-to-face interactions at the workplace. In short, when an innovation has at the same time positive and negative effects on individuals' well-being, how can we provide an ethical and normative assessment of the impact of that innovation? Is the innovation good or bad for individuals and social welfare – and should public policy promote its diffusion, or rather hamper and regulate it? These questions are paramount, but they are often neglected in standard academic and innovation policy approaches.

overall effects of specific innovation trajectories on human well-being calls for a twofold effort in future research. First, ethical and social values that are related to different positive and negative effects must be discussed and made explicit, in order to have a conceptual basis to compare distinct impacts, and argue whether and why some effects should be considered more important than others. Second, to the extent that relevant metrics and micro-level data and indicators are available, empirical research should seek to determine net effects of specific innovations by means of *ex-post* empirical/econometric analyses.

4. Time horizon of effects. As noted above, some innovation trajectories have arguably short-run and transitory effects on individuals' well-being, which progressively become less and less important over time because of habituation mechanisms and adaptation effects. For instance, the consumption of new varieties of a given product or service does initially lead to satisfy new preferences and increase hedonic well-being, but such increase will not be permanent and gradually fade away. By contrast, other types of innovation have impacts that tend to persist for a longer period of time because they foster objective dimensions of well-being, such as agents' capabilities, which are not subject to the same type of habituation effects as consumption activities and hedonic well-being. The interesting point here is that many innovations have at the same time short-run (transitory) and long-run (persistent) effects on well-being. This aspect is seldom studied in extant research, and it calls for an analysis of the intertemporal trade-offs between current and future well-being, and of how innovations affect such trade-offs.

5. Extent of impacts. The examples that I have presented also illustrate another important aspect. Some innovation trajectories affect a single and well-defined domain of life of individuals, thus having a narrower scope and impact (e.g. e-commerce affects mainly individuals' consumption activities). By contrast, other types of innovation have by their own nature a broader scope because they may affect different domains of life at the same time. In particular, the model has pointed out that innovations that foster capabilities and functioning (e.g. related to health and education) are in many respects more pervasive than others because they enable individuals to actively participate in all domains of life. Hence, they do not only foster hedonic well-being in a given domain of life, but they also create greater opportunities to enhance objective well-being in other spheres of life. The fact that some innovations can have more pervasive and extensive effects on well-being than others is seldom acknowledged in extant research and policy debate, and it should become a cornerstone of innovation studies and innovation policy.

6. Agents heterogeneity. Finally, another key conceptual and methodological challenge refers to the fact that agents are heterogenous in terms of endowment, capabilities and economic opportunities. This is an important aspect of the ABM model presented in the previous sections. Hence, it is reasonable to argue that the effects of a given innovation on well-being may be different for different individuals and socio-economic groups, precisely because such effects will also depend on, for instance, an individual's initial endowments, relative position in the income distribution, health conditions, and skills and education level. This means that if we seek to assess the overall impacts that a given innovation has on the well-being of the population, we need to have a conceptual framework that points out a theory of social justice that is able to assess and compare the relative importance of the well-being of different individuals and socio-economic groups. The economics of innovation has until now largely neglected the study of theories of social justice, and adopted a utilitarian notion that defines social welfare as the simple sum of all agents' well-being (Castellacci, 2022). Considering alternative theories of social justice, and developing social welfare functions that take into account efficiency as well as equity and distributional aspects, represent another major area for future research.[10]

6 Conclusions

The paper has presented a comprehensive analysis of the relationships between innovation and human well-being. The work is motivated by the fact that research in the economics of innovation has mostly focused on the positive economic effects of new technologies on agents' well-being, and typically neglected a variety of other important impacts that innovations have on well-being and welfare. Extant research on innovation and well-being is scant and fragmented. Different strands of research are developing separately from each other, and there is a need for a unified and comprehensive framework to guide further research on this theme. Further, from an empirical point of view, there is a puzzling question that this field of research should address. In the context of advanced economies, technological change has proceeded rapidly in the last decades, whereas data on well-being and life satisfaction indicate a mostly stagnant pattern. Current research on innovation and well-being does not provide any insight on this question, that is indeed important for both research and policy-making.

To spell out a broad and comprehensive conceptual framework, the paper has presented an agent-based model (ABM) of innovation and well-being. The ABM models a population of heterogenous agents whose well-being during their lifetime depends on the utility they derive from working life, on the one hand, and leisure activities, on the other. At any period, agents can allocate their time between work, education and leisure, and this allocation will have different implications in terms of their well-being from work and leisure. Empirically calibrating the model for the US economy, the simulation analysis points out that the aggregate long-run outcomes of the model are an increasing level of GDP per capita, stagnant average well-being and increasing disparities between rich and poor individuals. The main contribution of the model is that it points out and disentangles seven types of mechanisms that link innovation to well-being. The model shows that some of these mechanisms are crucially important for individual well-being, whereas others do only provide temporary, transitory and weak impacts. The ABM is thus meant to provide a general conceptual framework to study the effects of innovation on well-being, and to guide future research on this topic by pointing out novel directions of research, which section 5 has summarized and discussed.

The academic relevance of this research is that it seeks to contribute to a more holistic and comprehensive understanding of the relationships between innovation and well-being, thus combining insights from distinct and fragmented strands of research that are currently studying this topic from different perspectives, and without much interaction with each other. In general terms, our approach shows that further cross-fertilization between

[10]Points 1 to 5 noted in this section call for future research that will have to deal with the important issue of *intra-personal comparability* of utility and well-being. This means that, in order to compare and assess the relative importance of contrasting effects on the well-being of a given individual, this research will be based on a conceptual framework that allows intra-personal comparison for any given individual, and/or it will develop metrics and indicators that make intra-personal comparisons possible in empirical research. On the other hand, point 6 noted above requires a conceptual and empirical framework that enables *inter-personal comparability*, i.e. the possibility to compare (combine, aggregate) the utility and well-being of different individuals in the society. For a further discussion of intra-personal and inter-personal comparability, see Adler and Fleurbaey (2016).

the economics of innovation and well-being studies will contribute to advances of research on this important theme. How could this conceptual framework be applied and extended in future research? I envisage two complementary ways to use and further develop this model in the future.

First, more narrow and elaborated versions of this ABM could be developed to analyze further some of the different effects of innovation on well-being (e.g. new ABMs to study consumption-related effects; social communication effects; value-shaping effects), each new model contributing to a different field (e.g. economics of innovation; computer-human interactions; behavioral economics and psychology). Second, the model could be extended in future research to empirically analyze the case of specific innovation trajectories (e.g. automation, AI, social media, green innovations, medical technologies). Empirical analyses of this topic could exploit the availability of large datasets that provide rich information on individuals' well-being for a large number of countries in the world (Kahneman and Krueger, 2006; MacKerron, 2012; Nikolova and Popova, 2021). These available data sources may be linked with data on innovation (supply side innovation and capabilities; and/or demand-side use of new technologies), providing relevant empirical material to calibrate ABMs, testing some of the mechanisms that this paper has pointed out, and designing future scenarios for innovation policy (Castellacci, 2022).

The argument presented in this paper has potentially relevant normative implications. The main implication of our argument is that public policy should primarily promote and support the development and diffusion of innovations that enhance well-being, and hamper and regulate those that do not. Based on the discussion carried out in the paper, the innovations that are more important for well-being and that should be at the core of innovation policy support programs are those that: (i) promote agents' capabilities and functioning; (ii) contribute to foster individuals' ability to make independent value judgement and use critical thinking; (iii) have positive and long-run enduring impacts. By contrast, the innovations that are less relevant for well-being are those that: (i) foster unnecessary consumption and short-run satisfaction; (ii) foster material aspirations, income comparisons and a social «rat race»; (iii) may be used for the manipulation of individual thinking and value formation; (iv) present future risks for some socio-demographic groups that are not well understood yet at present. In short, a theory of innovation and well-being is meant to contribute to technology assessment, and to clarify the foundations and objectives of innovation policy.

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APPENDIX

Table A.1: Model's parameters: definition and numerical values

Parameter	**Definition**	**Range**	**Value**
N	Number of agents	$N > 0$	1000
α	Probability of innovation at time t	$[0; 100]$	3.5%
β	Effect of skills on probability to adopt innovations	$[0; 1]$	0.50
γ	Effect of peers on probability to adopt innovations	$[0; 100]$	50
a	Relative importance of work and leisure for well-being	$[0; 1]$	0.5
ε	Saving propensity	$[0; 1]$	0.08
δ	Fraction of agents that are considered peers	$[0; 1]$	1
b	Effect of consumption on well-being	$[0; 1]$	0.95
c	Relative income effect	$[0; 1]$	0.45
d	Adaptation effect	$[0; 1]$	0.40
$PE^{(W)}$	Quality of physical environment at work	$[0; 1000]$	10
$SE^{(W)}$	Quality of social environment at work	$[0; 1000]$	10
e	Effect of physical work environment on well-being at work	$[0; 10]$	0.10
f	Effect of social work environment on well-being at work	$[0; 10]$	0.10
F_S	Education fee	$[0; 100]$	10
g	Effect of skill level on wage level	$[0; 1]$	0.10
h	Effect of education investments on skill level	$[0; 1]$	0.10
K	Knowledge capital	$[0; 1]$	1
$PE^{(L)}$	Quality of physical environment for leisure	$[0; 1000]$	10
$SE^{(L)}$	Quality of social environment for leisure	$[0; 1000]$	10
l	Effect of leisure activities on well-being from leisure	$[0; 0.1]$	0.01
m	Effect of physical environment on well-being from leisure	$[0; 10]$	1
n	Effect of social environment on well-being from leisure	$[0; 10]$	1
o	Probability to get sick	$[0; 100]$	34%
p	Mortality rate	$[0; 100]$	0.88%
q	General fertility rate	$[0; 100]$	6.8%
r	Share of time allocated to productive activities	$[0; 1]$	0.7