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Conceptualizing the Impact of Information and Communication Technology on Individual Time and Energy Use

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Abstract

The energy requirements of everyday activities such as housework, travel or sleep differ considerably; hence, individual time use – the pattern of activities individuals perform during a day – is crucial for the energy consumption associated with lifestyles. Increasing use of information and communication technology (ICT) in everyday life changes individual time use and thus affects the associated energy requirements. ICT can have increasing or decreasing effects on energy use (e.g. it can reduce transport through virtual mobility or increase transport by creating the desire to travel to places seen on the Internet). Understanding the causal relationships between ICT, time, and energy use is essential to promote its desired impacts and prevent socially and environmentally unfavorable (unsustainable) ones. Despite various approaches to time use across disciplines, no consistent conceptual framework of the impact of ICT on time use and environmental impact exists so far. In this paper, we review existing literature on (1) ICT impacts on time use, and (2) environmental impacts of time use. Aiming to bridge differences across disciplines and methodological approaches, we develop a conceptual framework for systematically assessing the impact of ICT on time and energy use. The core of this framework is the categorization of ICT impacts on the relaxation of time and space constraints to activities, parallelization, fragmentation, substitution, avoidance, and delegation of activities, changes to the duration and manner of activities, changes to the process of activity planning, and generation of new ICT-based activities. In a broader systems perspective, these effects also trigger causal chains which can form feedback loops and thus change time-use patterns with some delay (systemic effects). Changes in time use affect direct energy requirements through the energy used to perform activities (e.g. in the form of electricity or fuels). Indirect energy requirements, the energy embedded in goods, only change if production of goods can be avoided (e.g. if telecommuting leads to fewer cars being purchased). The net energy impact of a given ICT use case depends on direct and indirect energy requirements of the activities performed before and after adoption of the use case. We demonstrate the application of the framework by qualitatively assessing time and energy use impacts of a frequently discussed ICT use case: telecommuting.

Keywords

Information and communication technology, time use, time allocation, activities, energy use, rebound effect.

Highlights

- Conceptual framework of causal relationships between ICT, time, and energy use
- Specification of ICT impacts on activity planning and execution
- Discussion of direct and indirect energy impacts of ICT-induced changes of time use
- Qualitative assessment of time and energy impacts of 'telecommuting'

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1. Introduction

The amount of time available to everyone, rich or poor, on any given day is equal and limited. How people use their time allows conclusions about their lifestyles and the state of society. Individual time use – the activities individuals perform on any given day – is not only a core aspect of lifestyle, it also has environmental consequences. For example, the greenhouse gas (GHG) emissions associated with a trip from Zurich to a meeting in Paris and back by plane are 10 times larger than accessing the same meeting by train and more than 300 times larger than having a virtual meeting using videoconferencing technology (Warland & Hilty, 2016).

Time use has been addressed in several academic disciplines. Specialized approaches have evolved, such as "time allocation theory" (economics), the "time-use approach" (economics), "time geography" (human geography), "time prosperity" (economics), "activity-based modeling" (engineering and technology), and "practice theory" (sociology) (Becker, 1965; Hägerstrand, 1985; Jalas, 2002; Heitkötter & Schneider, 2004; Giddens, 1984; Cascetta, 2009). Jalas' (2002) time-use approach is one of the few approaches which systematically address environmental impacts of time use. He defines a lifestyle as a "dynamic pattern of consumption activities" (p. 111) and estimates energy requirements of goods and services used to perform activities (e.g. commuting by car or even sleeping while heating the house are activities which require energy). Palm, Ellegård and Hellgren have developed an approach to estimate and visualize energy consumption of activity sequences performed by household members (Palm et al., 2018; Ellegård & Palm, 2011; Hellgren, 2015). Many subsequent studies have investigated the environmental impact of everyday activities and found that environmental impacts caused by activities such as sleep, travel, housework, or shopping differ considerably and that the individual patterns of allocating time to activities (time-use patterns) are crucial for the sustainability of lifestyles (Druckman et al., 2012; Jalas, 2002; Sekar et al., 2018). Figure 1 provides an illustrative example of the energy use of activities during one day.

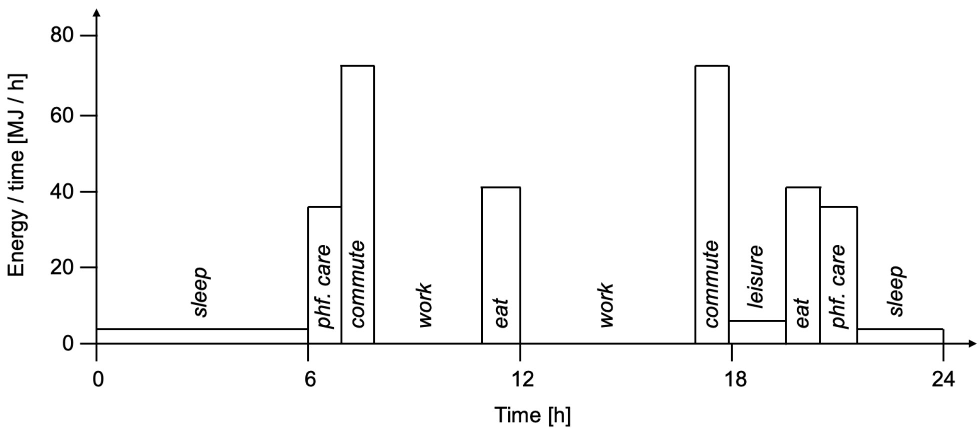

Figure 1: Illustrative example of time allocation and energy implications during one day, based on Jalas' study on energy requirements of activities of Finnish households 1998-2000 (Jalas, 2005). "Phf. care" means personal, household, and family care (e.g. washing laundry). Energy requirements for sleep (e.g. due to heating) are estimated by the authors since the original study does not include them. The energy requirements of work are zero because in a consumption-oriented perspective, all energy requirements of producing goods and services are allocated to their final consumption.

Information and communication technology (ICT) has penetrated society to an extent that lets people structure their lives around the possibilities it provides – a process called digitalization (Brennen & Kreiss, 2014). ICT's impact on the environment has been addressed in the literature (Asadi et al., 2017; Añón Higón et al., 2017; Bieser & Hilty, 2018b; Bieser & Hilty, 2018c) as well as ICT's impact on time use (and thus on the environment), for example:

- ICT can help us save time and reduce environmental impacts, e.g. by replacing physical travel with virtual mobility (Bieser & Hilty, 2018a; Coroama et al., 2012; Hilty & Bieser, 2017).
- ICT can "make information about people and activities much more accessible" and therefore create the "desire to travel to participate in those activities and interact with those people" (Mokhtarian, 1990: 235).
- Certain amounts of energy, time, and information are needed to produce any good or service (Spreng's Triangle) and ICT increases the use of information, which can reduce energy and/or time needs (Spreng, 2015; Spreng, 2001).
- ICT impacts the time efficiency of activities and can increase the pace of life, i.e. "the speed and compression of actions and experiences" (Rosa, 2003: 8/9; Wajcman, 2008), which can have positive or negative environmental consequences. This depends on how the time saved on one activity is used for others, a crucial idea of our approach.

These examples show that ICT can have diverse impacts on individual time use and thereby reduce and/or increase environmental loads. Understanding the causal relationships between ICT, time-use, and environmental impact is essential to promote its desired impacts and prevent socially and environmentally unfavorable (unsustainable) ones. Existing approaches to time use and the associated environmental impacts represent a variety of perspectives and focus on different aspects; however, no consistent conceptual framework of the impact of ICT on time use and environmental impact exists so far. In this paper, we develop a framework of ICT impacts on time and energy use. The framework provides harmonized terminology across disciplines and allows researchers to identify, structure, and analyze potential ICT impacts systematically. It thereby supports the assessment and discussion of ICT applications, especially from the perspective of environmental impacts.

2. Approach

In this paper, we…

(1) review existing literature on the impact of ICT on individual time use and structure it according to different areas of life (leisure, work, maintenance, and transport),
(2) discuss the relationships between lifestyles, activities, and energy requirements from a time-use perspective,
(3) develop a conceptual framework for ICT impacts on individual time use (specifically on activity planning and execution) and discuss the implications for energy use, and
(4) demonstrate the application of the framework with an example use case: telecommuting.

We build the framework based on existing literature on ICT and time use as well as Jalas' time-use approach because it explicitly quantifies direct and indirect ICT energy impacts from a time-use perspective. To do so, we identify basic mechanisms of ICT impacts on time and energy use which apply to all areas of life and harmonize terminology across approaches in different disciplines.

3. ICT impacts on time use

Various hierarchies of abstraction for describing everyday activities exist, ranging from a low abstraction level (activities, e.g. "playing football") to a medium level (activity categories, e.g. "doing sports") to a top abstraction level with only a few broad categories (areas of life, e.g. "leisure").

In the following, we provide an overview of studies describing ICT impacts on time use, structured according to a high abstraction level: leisure, work and maintenance activities. We add a section on transport, as it is a widely discussed application domain of ICT which interacts with time use in all areas of life.

3.1 Leisure

Various definitions for leisure activities exist, centering around three aspects: (i) leisure activity needs to be pleasant and freely chosen; (ii) the output of leisure activity is not marketable; and (iii) leisure activity "is consumed simultaneously and therefore cannot be delegated to anybody else" (third person criterion) (Beblo, 2001: 2; Mokhtarian et al., 2006; Tinsley et al., 1993).

Mokhtarian et al. (2006) investigate the impact of ICT on leisure and related travel and identify four types of ICT impacts on leisure activities:

- Replacement of traditional leisure activities with ICT-based counterparts (e.g. substituting cinema with DVDs),
- Generation of new ICT activities (e.g. surfing the Internet),
- ICT-enabled reallocation of time to other activities (e.g. commuting time saved through telecommuting may be allocated to leisure activities), and
- ICT as enabler/facilitator/modifier of leisure activities (e.g. ICT provides access to large amounts of information about possible leisure activities and facilitates communication).

Regardless of the type of impact, the motivation for performing a leisure activity determines "which kinds of leisure activities are more likely to be impacted by ICT" (Mokhtarian et al., 2006: 267). For example, activities aiming at physical exertion (e.g. swimming) or sensual enjoyment are potentially not substituted through ICT-based counterparts. For activities of cognitive stimulation (e.g. art galleries) or creative activities (e.g. painting) "ICT may provide a new dimension to the participation in these activities," e.g. through virtual mobility (Mokhtarian et al., 2006: 267).

3.2 Work

Work, or labor, is one of the inputs needed to produce useful output and usually "includes all activities that do not have to be performed by a particular individual" (Beblo, 2001: 2). Lee (2016: 1) summarizes various impacts of ICT on work, e.g. ICT can disrupt or change business models, loosen up traditional boundaries between companies, and change "place and time […], as well as content, structure and the process of work". Routine jobs are replaced by machines and work "is now more cognitively complex, more team based, more dependent on social skills […] and technological competence, more time pressured, and more mobile" (p. 2).

With respect to time use, ICT fragments the activity work – it allows us to perform activities at different places and times (Couclelis, 2000). Virtual mobility solutions can eradicate the need for work-related travel (e.g. through teleconferencing, remote maintenance). ICT can allow workers to fit working hours to personal preferences, e.g. by increasing flexibility in time and place of work (Leung & Zhang, 2017). However, there are arguments that digital technologies can increase workload, pressure people to multitask, harm work-life balance, raise stress levels and affect human health (Barnett et al., 2011; Leung & Lee, 2005).

3.3 Maintenance

Maintenance activities such as chores or personal care are often not performed voluntarily (in contrast to leisure) and do not involve the exchange of time for money (in contrast to work) (Beblo, 2001; Mokhtarian et al., 2006).

ICT impacts on maintenance activities are less researched than on leisure or work activities. Røpke et al. (2008) discuss the impact of ICT on household energy use and state that ICT creates additional maintenance activities, namely ICT maintenance. Lenz and Nobis (2007) find that many people who use ICT also fragment private activities, in particular shopping. Choudrie and Dwivedi (2007) investigate the impact of broadband Internet on 20 everyday activities in UK in 2004/2005, four of which can be considered maintenance activities (shopping in stores, housework, time with family, receiving/making phone calls). They find that broadband users spend less time on in-store shopping than narrowband users, but time spent on housework did not differ significantly.

The increasing diffusion of smart home solutions creates additional types of impacts on maintenance activities, e.g. through automation of household tasks (e.g. robotic vacuum cleaners) or remote control (e.g. controlling room temperature from outside the home). Energy efficiency improvements of household appliances (which today are often enabled by making the appliances "smart") can also lead to increased use of such appliances (Woersdorfer, 2010).

3.4 Transport

Researchers from several disciplines have addressed the question how ICT changes transport demand, modal split, the efficiency of transport, transport infrastructures, and vehicles; these issues, explicitly or implicitly, are also connected to individuals' time use. In a review of research on the relationship between telecommunications and travel, Salomon (1986) discusses two conceptual relationships,

- telecommunications substituting transport and
- telecommunications enhancing transport,

concluding that the relationship between telecommunications and transportation is not unidirectional. Similarly, Mokhtarian et al. (2006) investigate the impact of ICT on leisure activities and related travel and find that "[f]or some types of effects […] the adoption of ICT is likely to reduce travel; for others […] the primary effect is likely to be generation of new travel" (p. 282).

In her seminal work, Mokhtarian (1990) discusses the supply-demand relationship between transport and telecommunication. According to her, telecommunications can

- increase efficiency of transport supply (e.g. through traffic routing systems),
- reduce transport demand (e.g. through substituting physical commuting with telecommuting) or
- increase transport demand (e.g. through making "information about people and activities much more accessible" and creating "the desire to travel to participate in […] activities and interact with […] people" (p. 235). This phenomenon is also discussed by Fortunati and Taipale (2017).

Couclelis (2000) discusses the impact of ICT on fragmentation of activities and implications for travel. Here "fragmentation" means the interruption of one activity by another activity and the subsequent continuation of the former. Through ICT, more and more activities are no longer bound to particular times of day and/or places. As a consequence, the individual's flexibility in building chains of activities increases, which may lead to greater transport demand. Lenz and Nobis find that in 2003 in Germany specific lifestyles (e.g. those of people who rely on mobile phones or computers for work, because they travel for work or work from home) are more prone to fragmentation than others (e.g. those of conventional full-time workers). However, they hypothesize that it might not be that "ICT use […] has an impact on travel behavior, but high travel frequency induces demand for ICT" (pp. 202f.).

Wang and Law (2007) conducted an empirical study on the impact of ICT use on travel time and behavior in Hong Kong. They found that the use of ICT leads to more trips and increases the time spent for travel. Hilty et al. (2004, 2006) conducted a simulation study on impacts of ICT on the environment which indicates that ICT makes transport more efficient and that virtual mobility such as telecommuting or virtual meetings "serves as a loophole when the time used for travel tends to exceed an acceptable limit" (p. 1626). The model also took into account that ICT enables "better possibilities for time utilization during transport" (p. 1626).

Several inconsistencies can be found among the results of studies investigating ICT impact on transport. For example, assessments of telecommuting, videoconferencing, e-health, or e-commerce usually conclude that ICT use decreases the need for travel (GeSI & Accenture Strategy, 2015). In contrast, studies investigating the systemic relationship between ICT and travel find that ICT might also increase travel demand (Mokhtarian, 1990; Mokhtarian et al., 2006; Salomon, 1986). Differences in results can be explained by different system boundaries: studies of specific ICT use cases (e.g.

substitution of physical commuting with telecommuting) often assume a relatively narrow system boundary, e.g. they investigate immediate impacts associated with the use case while neglecting feedback loops that become apparent in a broader systems perspective and can create rebound effects (e.g. time saved on commuting will be spent on other activities, or transport demand is not constant) (Bieser & Hilty, 2018a; Bieser et al., 2019; Ahmadi Achachlouei & Hilty, 2014).

4. ICT energy and climate impacts from a time-use perspective

In the following we discuss the causal relationships between ICT, time use, energy use (and resulting GHG emissions) based on Jalas' time-use approach. Jalas' approach was chosen because it systematically addresses environmental impacts of time use.

4.1 Environmental impacts of time use

In his seminal article on the time-use approach, Jalas (2002: 111) defines lifestyles as a "dynamic pattern of consumption activities" (p. 111). He allocates household expenditure, energy consumption, and input-output data to temporal activities and estimates the direct and indirect energy requirements of activities per hour (e.g. 83 MJ/h for leisure-time travel, 16 MJ/h for housework, 3 MJ/h for reading). Direct energy requirements represent the direct consumption of energy carriers during the performance of an activity. These include fuel consumption of transport vehicles, fuel or electricity consumption for heating and cooling buildings (e.g. oil, gas, electricity), and electricity consumption of electrical and electronic appliances (e.g. stoves, lights, TV sets). Indirect energy requirements are embedded energy, i.e. the "energy use of producing the goods and services that are needed in the activity" (e.g. production of a car) (Jalas, 2002: 114). The time geography approach by Palm, Ellegård and Hellgreen also connects energy requirements with activities. In contrast to Jalas' time-use approach, it focuses on the analysis of activity sequences and their direct energy requirements (Ellegård & Palm, 2011; Palm et al., 2018; Hellgren, 2015).

Many researchers have followed this approach. For example, Aal (2011) estimated the energy requirements of leisure activities in Norway in 2001, Minx and Baiocchi (2009) estimated activity material requirements in West Germany in 1990, Yu et al. (2019) estimated activity CO_2 emissions in China in 2008, Druckmann et al. (2012) estimated activity GHG emissions in Great Britain in 2005 and Smetschka et al. (2019) estimated activity GHG emissions in Austria in 2010. In recent years, the energy requirements of new ICT-based, especially online, activities (e.g. video streaming) have gained attention (Coroama et al., 2015; Hilty & Aebischer, 2015; Kern et al., 2018).

4.2 ICT energy impacts from a time-use perspective

From a time-use perspective, net energy impacts of ICT depend on the energy requirements of the activities performed before and after adoption of an ICT use case (e.g. telecommuting, e-commerce). Changes in time allocation have an immediate impact on direct energy requirements. For example, driving an average car for 30 additional minutes at 30 km/h directly increases energy consumption by 35.7 MJ. However, driving for 30 additional minutes has no immediate effect on indirect energy requirements, in this case the energy required to produce the car. Only if the utilization of a durable good – the share of time the good is in productive use – increases does the indirect energy requirement per time unit decrease; yet total indirect energy requirements remain constant. However, if utilization of a good drops so low that a person decides to stop owning such a good, indirect energy requirements are avoided. For example, if someone bought a car mainly for commuting to work, telecommuting might reduce his or her use of the car to such an extent that he or she might sell the car or not buy a new one after it reaches the end of its service life.

ICT time rebound effects occur when ICT-enabled increases in time efficiency lead to an increase in energy use. Sorrel and Dimitropoulos (2008: 644) argue that consumers can choose "between energy services with different levels of time and energy efficiency" (e.g. walking vs. driving a car) and that due to "time costs forming a significant proportion of the total cost of many energy services, consumers and producers have sought ways to improve the time efficiency, rather than the energy efficiency".

5. A conceptual framework for assessing ICT impacts on time and energy use

In the following, we develop a conceptual framework of ICT impact patterns on time and energy use. Based on the literature summarized in chapter 3, we distinguish between immediate impacts of ICT on planning and execution of activities (see 5.1) and systemic effects with consequences for time use (see 5.2). We discuss the implications of these impact patterns for direct and indirect energy use (see 5.3.) based on the causal relationships between ICT, time, and energy use described in section 4.

5.1 Impacts of ICT on activity planning and execution

We distinguish two phases in an observed timeframe, namely activity planning and activity execution:

- Activity planning: the process of selecting and scheduling the activities to be performed for a specific time horizon (Cascetta, 2009). Activity planning can be performed implicitly or explicitly and take from almost none up to a significant amount of time.
- Activity execution: the performance of the planned activities

Each time an individual plans, he or she selects and schedules one or more activities within a certain time horizon of planning (planning horizon). Each activity has a unique starting point, duration, and location (figure 2).

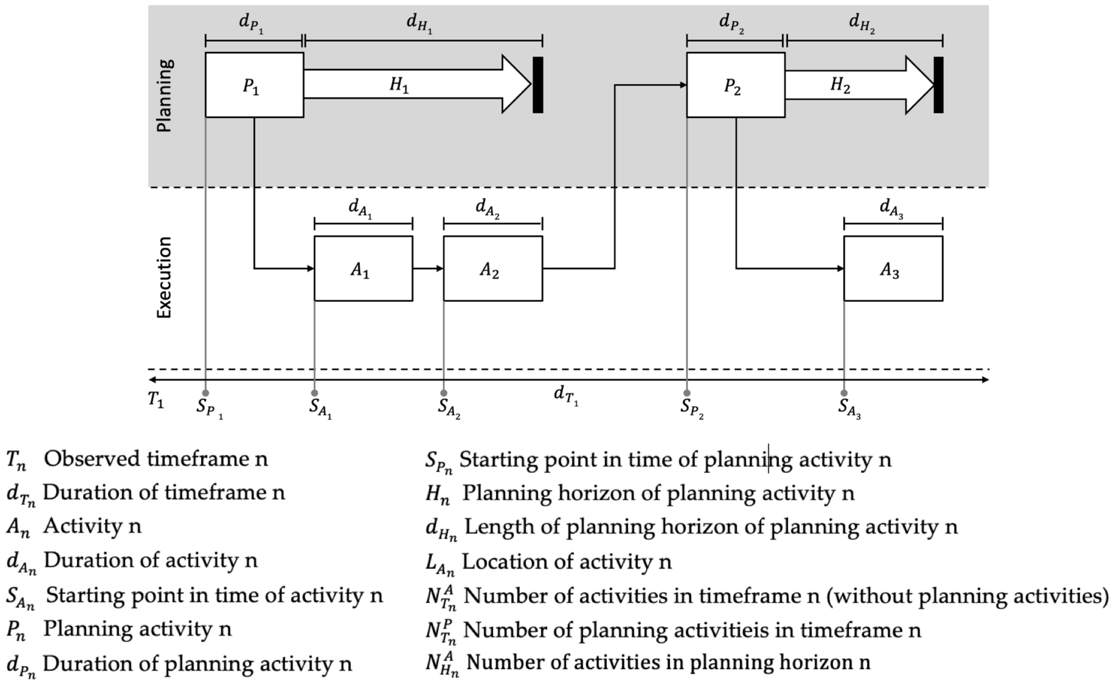

Figure 2: Conceptual framework of activity planning and execution over time (source: authors).

ICT impacts both activity planning (selection, scheduling, planning horizon/duration/frequency) and activity execution (manner, duration, fragmentation). Table 1 summarizes the impacts we describe in the following. Figure 3 provides a graphical representation of six patterns of ICT impact on activity planning and execution.

Phase	Aspect	Guiding question(s)	ICT impact pattern
Activity planning	Activity selection	Which activities will I perform?	- Substituting activities - Avoiding activities - Delegating activities - Creating additional activities
	Activity scheduling	When will I perform activities? Where will I perform activities?	- Relaxation of time constraints - Relaxation of space constraints - Parallelization
	Planning horizon, duration and frequency	How long do I plan in advance? How much time do I spend on planning? How often do I plan activities?	- Shorter/longer planning horizon - Less/more time spent on planning - More frequent replanning
Activity execution	Activity manner	How do I perform an activity?	- Impact highly activity-specific - E.g. decreasing/increasing complexity of the activity
	Activity duration	How long does an activity take?	- Shorter/longer activity duration
	Activity fragmentation	Do I complete an activity once I started it?	- Interrupting activities - Increasing focus on activities

Table 1: ICT impact patterns on activity planning and execution

5.1.1 Activity selection

ICT can change the activities people perform by substituting, avoiding, or delegating activities, as well as by creating additional (ICT-based) activities. For example, ICT can replace a physical visit to the local bank branch with an e-banking session (substitution) and eradicate the need to travel to the bank branch (avoiding). Another example is e-commerce, which allows individuals to avoid trips to physical stores; the goods are transported to the home by a logistics service provider (delegation).

ICT use cases may also add to the list of potential activities themselves (e.g. surfing the Internet, video streaming, browsing social media).

5.1.2 Activity scheduling

ICT use leads to a relaxation of both time and space constraints to be considered in activity scheduling:

- Relaxing time constraints: Many activities which originally had to take place during specific time periods can be performed flexibly at any time (e.g. opening hours of banks vs. e-banking).
- Relaxing space constraints: Activities that used to be tied to one or a few locations can be carried out at additional locations (e.g. working from home).

A consequence of relaxed time and space constraints is that there are more options to perform activities simultaneously. If someone writes an article on the train, working and traveling activities are parallelized. Røpke and Christensen (2012: 355) state that ICT can also lead to "activation of 'dead time'" (e.g. surfing the Internet while waiting for the bus).

5.1.3 Planning horizon, duration, and frequency

The time spent on planning can potentially be shortened or prolonged through ICT. On one hand, ICT can save time spent on planning by enabling the user to gather information required for planning faster (e.g. with a calendar app) or by automating parts of the planning process. On the other hand, ICT can increase the time spent on planning. For example, online travel guides (e.g. TripAdvisor or Foursquare) provide an overwhelming number of options for sightseeing activities, hotels, and restaurants. Instead of choosing one out of a few options listed in a conventional, paper-based travel guide, individuals might compare a large number of alternatives and maybe even suggestions from various online travel guides. Also, ICT increases individuals' flexibility in building chains of activities: the more options there are, the harder it is to choose and the more time is needed to make an optimal or at least a "good enough" decision. Furthermore, the relaxation of time and space constraints mentioned above can reduce the need for planning or the complexity of the planning process.

ICT can also change the planning horizon. Again, this can go in both directions. If ICT-based solutions provide the user with better forecasts (e.g. traffic or weather forecasts), this reduces uncertainty about the future and could enable users to extend their planning horizon. However, mobile connectivity also weakens the requirement to commit to a plan in advance because coordination with others is possible at short notice. People can therefore plan activities more spontaneously, after waiting for the best available information before choosing the preferred alternative. The possibility to communicate with anyone at any place at any time can thus trigger frequent replanning of activities as people can more flexibly change or cancel commitments already made. Even before the classical mobile phones were replaced by smartphones, Mokhtarian et al. (2006: 279) stated that "mobile phones permit an impulsivity of activity engagement (spontaneous arrangement of meetings; last-minute reservations) that was not previously possible (or at least not easy)".

That ICT would reduce the frequency of replanning is less plausible, and we could not find any evidence in the literature for this effect.

5.1.4 Activity manner

ICT also changes the manner of performing activities, i.e. the activities themselves. For example, film cutting used to be done with scissors and the processing possibilities were limited, while digital video processing provides numerous processing possibilities, such as filters or even 3D-effects. The actual impact of ICT on the way of doing things is highly activity-specific.

5.1.5 Activity duration

ICT also changes the time needed to perform activities. In many cases, the time decreases due to ICT-enabled efficiency gains. For example, due to navigation systems, car drivers can find the fastest travel route and use live traffic information to avoid traffic jams. In other cases, the extra time needed to set up and maintain ICT solutions supporting the activity, deal with security issues and the consequences of software errors can compensate or even overcompensate for the efficiency gain expected from using the solution.

5.1.6 Activity fragmentation

The relaxation of time and space constraints through ICT has the side effect of creating options to fragment activities. Formerly uninterrupted activities are now broken up into pieces which are performed at different times and places (temporal and spatial fragmentation). For example, conventional office workers commonly went to work in the morning and home in the evening; their work activity was interrupted only by their lunch break. Today, someone's work day might be fragmented into time spent working at home in the morning (writing a report), at the office in the afternoon (meetings), and at a friend's house in the evening (e-mail), with non-work activities in between. Activity fragmentation can also occur when ICT distracts our attention from activities, thereby interrupting them, especially if people continuously receive incoming communications and information updates on various digital channels (e.g. email, SMS, WhatsApp, LinkedIN, Facebook, Instagram, Tinder). In contrast, mobile work enables people to choose their working locations freely and intentionally select locations in which interruptions are improbable.

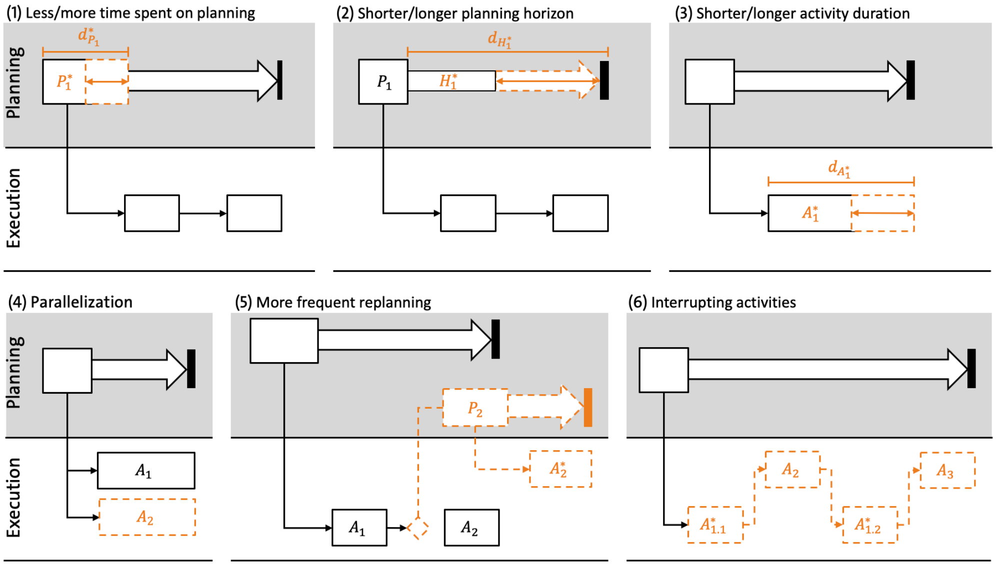

Figure 3: Selected ICT impact patterns on activity planning and execution (source: authors).

5.2 Systemic ICT effects on time use

Systemic effects of ICT on time use are effects which only occur through the relationships between variables in the broader system in which the ICT use case takes place. Specifically, ICT impacts on time use can trigger causal chains which form feedback loops. Thus, changes in time use can trigger other changes in time use with some delay. For example, given that telecommuting reduces time spent on commuting and adds flexibility to time and place of work ("flexiplace" and "flexitime"), it may influence families' decisions regarding where to live, jobs, investments in their dwellings and vehicles, simply because longer commuting distances become more acceptable (Salomon, 1986; Schiff, 1983). If this results in, for example, living in a rural instead of an urban area, this feeds back on individual time use, e.g. time spent on traveling for groceries, the mode of travel, or the type of leisure activities. In the long term, such developments can even lead to changes in land use patterns, such as "more decentralized and lower-density land use patterns" (Mokhtarian, 2009: 12).

Due to such systemic effects, the long-term consequences of ICT impacts on time use are difficult to predict. In an assessment of such effects, additional variables and their interactions need to be considered. This significantly increases the complexity of the problem and requires systems thinking and complex systems modeling.

5.3 Implications for energy requirements

The direct energy impact of ICT-induced changes in time allocation is the difference between the sum of energy requirements of the activities performed before and after the adoption of the ICT use case under study. If activities with high direct energy requirements are replaced with activities with low direct energy requirements (e.g. physical travel with virtual mobility), net energy requirements decrease – and vice versa. Most motorized transport activities (e.g. car, public transport) have relatively high direct energy requirements, whereas nonmotorized transport (e.g. bicycle, walking), common leisure (e.g. reading, watching TV) or maintenance activities (e.g. cleaning) have relatively low direct energy requirements (Druckman et al., 2012; Jalas, 2002). In table 2, we describe the direct energy impacts of ICT impact patterns on activity planning and execution.

Phase	Aspect	ICT impact pattern	Direct energy impacts
Activity planning	Activity selection	Substituting activities	If high-energy activities are replaced with low-energy activities, net energy requirements decrease – and vice versa.
		Avoiding activities	Energy requirements associated with avoided activity are avoided.
		Delegating activities	Only leads to changes in direct energy requirements if activity manner and/or duration change as well.
		Creating additional activities	Additional energy requirements associated with new activity. Reduction of energy requirements if new activity substitutes other activity.
	Activity scheduling	Relaxation of time constraints	No impacts if activity duration and manner do not change. However, relaxed constraints increase individuals' flexibility in building chains of activities with potential impacts on activity selection, duration, and energy use (e.g. working from home can induce additional shopping trips which otherwise could have been combined with commuting).
		Relaxation of space constraints	
		Parallelization	More activities can be performed in the same time frame. Additional energy requirements associated with additional activity.
	Planning horizon, duration and frequency	Shorter/longer planning horizon	Change in planning horizon, duration, and frequency only impacts direct and indirect energy requirements if activity selection, duration, or manner changes.
		Less/more time spent on planning	
		More frequent replanning	
Activity execution	Activity manner	Impact highly activity-specific	Depend on goods and services used before and after the change of activity manner (e.g. in contrast to traditional film cutting, digital video processing requires computers which consume electricity).
	Activity duration	Shorter/longer activity duration	Direct energy requirements decrease/increase with time spent on activity (e.g. driving a car longer increases total fuel consumption).
	Activity fragmentation	Interrupting activities	Activity fragmentation only impacts direct and indirect energy requirements if activity selection, duration, or manner changes.
		Increasing focus on activities	

Table 2: Direct energy impacts of ICT impact patterns on activity planning and execution.

Indirect energy requirements depend mainly on purchase of goods and services used to perform an activity, including the use of infrastructures which need to be built and maintained. Changes in time allocation only impact indirect energy requirements if they trigger additional production (e.g. buying an additional desktop computer to work from home) or avoids production (e.g. not purchasing a car because of telecommuting). With respect to infrastructure use, if ICT based solutions lead to a long-term change in demand for infrastructures, changes in building and operation of infrastructures can be expected.

The energy implications of systemic ICT impacts on time use depend on the nature of the change.

6. Example application of the framework

ICT provides the potential to reduce travel demand by replacing physical presence by virtual presence and by providing remote access to data. One important use case of this substitution is to replace physical commuting by telecommuting (in particular by working from home). In the following, we demonstrate the approach by qualitatively applying the framework to telecommuting. We focus mainly on impacts on activity planning and execution and associated energy requirements; and only sparsely on systemic impacts because they are more difficult to predict and less research has been conducted in this field.

6.1 *Activity selection*

By working from home, telecommuters can avoid the trip to work and associated direct energy requirements (Mokhtarian et al., 1995). Indirect energy requirements of commuting decrease if telecommuters decide to give up or not purchase a vehicle (e.g. car, motorcycle) or if demand for transport infrastructure decreases. The energy reductions due to avoided transport depend mainly on the choice of transport mode, commuting distance, traffic congestion, and telecommuting frequency (Kitou & Horvath, 2003; Mokhtarian et al., 1995). In the long run, changes in transport demand due to telecommuting can impact the supply of transport infrastructure and services and thereby also influence modal split and finally, in a feedback loop, individuals' time use (systemic effects) (Mokhtarian et al., 1995).

Time saved on commuting will be spent on other substitute activities. If commuting is substituted with travel for other purposes, no larger changes of energy requirements can be expected (assuming the same transport modes are used). If commuting is substituted with non-transport activities, a decrease in energy requirements can be expected because transport has higher direct and indirect energy requirements than most other common activities (e.g. for "leisure" or "personal, household and family care") (Jalas, 2002; Bieser et al., 2020).

6.2 *Activity scheduling*

Telecommuting relaxes time constraints of work. For example, some telecommuters can work early in the morning or at night when the employer's office might be closed. However, if the time spent on work remains constant, no larger changes in energy requirements due to relaxed time constraints can be expected.

Telecommuting also relaxes space constraints of work; in particular, people can work from home instead of the employer's office. This can increase residential energy consumption (e.g. due to additional heating and lighting at home). Mokhtarian et al. (1995) summarize early studies which consider household energy impacts of telecommuting and conclude that increases in residential energy consumption account for 11-25% of travel energy savings. Plus, telecommuting can also reduce energy consumption at the employer's office (e.g. less lighting and heating required, reduction in office space) (Robèrt & Börjesson, 2006).

If a larger share of workers telecommutes and telecommuters and employers reconsider their place of residence or business due to changes in commuting frequency, then living and office space requirements as well as changes in land use patterns can occur (systemic effects) with consequences for time and energy use (e.g. due to changes in travel distances) (Mokhtarian et al., 1995). However, de Abreu e Silva and Melo (2018) conclude that workers' residential location decisions (and the associated commuting distance) influences the choice whether to telecommute or not – and not vice versa.

6.3 *Planning horizon, duration, and frequency*

We could not find studies on impacts of telecommuting on planning horizon, duration, and frequency.

6.4 *Activity manner*

Telecommuting changes the way of working, e.g. because telecommuters conduct virtual instead of physical meetings to collaborate with colleagues. This increases use of ICT infrastructures with consequences for energy requirements. Kitou and Horvath (2003) estimated that changes in use of computers, copiers, printers, and fax machines at home and at the workplaces due to telecommuting have a small impact on energy requirements compared to energy impacts of avoided commuting; however, they did not consider additional ICT collaboration platforms and tools which might be required due to telecommuting.

Telecommuters might also perform other work activities when they work from home (e.g. more individual work at home, more collaborative work in the office). The energy impacts of this change are difficult to estimate.

6.5 Activity duration

People might spend more or less time on working when telecommuting (e.g. less time because they are less interrupted by colleagues and can focus on their work; more time because of the possibility to also work at times when the employer's office is closed). Energy impacts depend on the (substitute) activities more/less time is allocated to (see *activity selection*).

6.6 Activity fragmentation

Telecommuters can experience fewer interruptions when working from home because of the physical distance to colleagues. However, ICT collaboration tools (e.g. e-mail, messaging services) can also interrupt telecommuters if colleagues often send messages or call. The energy impacts of these changes depend on changes in the activity duration of work and consequences for other activities.

6.7 Overall assessment

To summarize, most changes in energy requirements of telecommuting depend on changes in activity selection, scheduling, and duration. As transport is an activity with higher direct and indirect energy requirements than most other activities, a net decrease in energy requirements through telecommuting can be expected from a time use perspective. However, systemic effects of telecommuting (e.g. due to changing land use patterns) are difficult to predict, and more research in this field is required for a final conclusion.

7. Conclusion

In this paper, we presented a framework of the causal relationships between ICT, time, and energy use based on existing literature on the impact of ICT on time use and on Jalas' time-use approach. The framework provides an interdisciplinary terminology to identify and describe ICT impacts on time use and systematically assess its consequential effects on energy use (or other environmental impact categories).

The framework describes ICT impacts on activity execution and planning in some detail. Systemic ICT impacts on time use, however, are described on a more abstract level because they depend on the interaction between variables in the broader use case system and are more difficult to predict. In order to include such effects into the assessment, long-term empirical studies and complex system models would be required. Most existing approaches for assessing the environmental impacts of time use allocate environmental impacts to the person who performs the activity, whereas many activities serve further people (e.g. cleaning benefits all household members).

Our qualitative demonstration of the approach for the use case 'telecommuting' indicates that telecommuting has the potential to reduced net energy use because transport has higher direct and indirect energy requirements than most common activities. A comprehensive environmental assessment of the most important ICT use cases from a time-use perspective requires detailed data on ICT-induced changes in time allocation to activities and associated impacts on energy use. We would therefore recommend this for future research.

We encourage researchers to apply our framework to investigate environmental effects of ICT from a time-use perspective and to provide more empirical evidence on this matter. Only if such effects are included in the environmental and social assessment of increasing ICT use can we develop measures to harness the potential of ICT to increase quality of life and protect the environment.

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