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Pathways for sustainable technology development - The case of bicycle mobility in Berlin

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Abstract

Sustainability requires that quality of life and resource consumption are harmonized. The use of sustainable technologies fosters their harmonization. A scenario based method has been developed for identifying sustainable technology systems on different levels of development and in different areas of human living. The developed method consists of four elements: the surrounding field scenarios, technology pool, sustainability assessment and system creation. They can be applied in various paths with different starting points. The two technology induced paths, emanating from either a system or a system element, enable the transformation of technological potentials into useful applications. The problem induced path, emanating from future framework conditions of an observed field, allows human needs to be satisfied trough technological potentials.
The application shown in this paper illustrates the usage of the method's problem induced path in mobility as one area of human living. Based on three surrounding field scenarios for bicycle mobility in Berlin, technology systems for bicycle design, operation and their repair in self-help workshops are illustrated.

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Keywords: Sustainability; future studies; concepts for bicycle mobility

1. Introduction

Sustainability, in terms of its environmental, social and economic dimension, requires that quality of life and resource consumption are harmonized [1]. The use of sustainable technologies fosters their harmonization. A scenario based method has been developed for identifying sustainable technology systems. This method is presented in the following, as well as the system creation and application of the method in the field of bicycle mobility in the city of Berlin.

1.1. Sustainability challenge

Today over 7 billion people are living on earth using 1.5 times more resources than earth can provide [2]. The challenge is to avoid the irresponsible path of the emerging countries increasing the quality of life by an increased resource consumption and at the same time not radically reducing the resource consumption of the early industrialized countries while maintaining an acceptable standard of living. The key is innovation, influenced by resource-efficient technologies, intelligent products, new service-systems and their combination with products as well as the enhancement of the productivity in conveying the challenge of sustainability [1]. While out of this twofold challenge the method presented can be applied in both areas, the concrete application of this paper is focusing on an exemplary chosen early industrialized country. One of the multiple approaches to harmonizing the quality of life with a responsible resource consumption explored within this paper is the approach of selling functionality instead of tangible products and using innovative production and learning systems.

1.2. Mobility as an area of human living

To be able to describe the different areas in which the method can be applied, the definition of “areas of human living” is used. Area of human living is understood as the prescientific implicitness [3] and the world in its sociological interpretation characterized by the individual perception [4]. The diverse areas of human living represent different overlapping perspectives on the world of human living with

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many intersections. The world of human living is defined within the framework of this paper as the individual perception with respect to the socio-cultural background [5]. Exemplary areas of human living are “mobility”, “energy” and “production”, whereas mobility and energy are seen as basis as well as result of the production in the sense of products.

Mobility is one of the key areas of human living and vital for modern economies, providing jobs and access to recreational activities. At the same time mobility at its current state is creating a huge negative impact on the environment and human health. According to the World Health Organization 24% of total greenhouse gas emissions in Europe and North America account to the transportation sector, contributing to the climate change but also causing health issues due to air pollution. One way to decrease these emissions is fostering the use of bicycles. In Europe, Berlin lies above average with a modal share of cycling of around 13%, but still way beyond Copenhagen (26%) and Amsterdam (33%) [6]. While this is a good starting point there still is a high potential for improvement in health and environmental aspects as well as creating new green jobs.

While the future development of mobility, even in a rather zoned area like Berlin, is very volatile, scenarios provide a chance to handle this uncertainty by describing different consistent pictures of the future.

The exemplary applications of the method presented in this paper have been created with the goal to develop bicycle design specifications according to the different surrounding field scenarios and to develop a system for bicycle operation and repair. The aspect of infrastructure has been integrated as an underlying assumption in form of a fixed framework condition. On this basis the applications have been elaborated with respect to how a sustainable bicycle design could look like and how a bicycle operation and repair system should be shaped to cope with the specific chances and risks of the provided surrounding field scenarios.

2. State of the art

To develop the method for finding sustainable pathways three fields of methods as well as their interception have been reviewed with regard to the overall goal: future studies, sustainability assessment and product development. 15 methods out of these areas and their interceptions have been analyzed regarding their applicability to identify and develop sustainable technological solutions for different levels of development. In the area of future studies [7] these are the delphi method, the trend analysis and the scenario technique. In the area of sustainability assessment these are the life cycle assessment (LCA), the product line analysis, the product carbon footprint, the cost-benefit analysis and the value benefit analysis. In the area of product development these are the guideline of the association of German engineers no. 2221 (VDI 2221), the theory of inventive problem solving (TRIZ/TIPS), the morphological analysis and the Pahl and Beitz design methodology. In the twofold interception spaces between these three areas the methods technology scenarios, eco-design and technology assessment have been reviewed [5]. While none of the existing methods fulfil the stated goal, parts of these existing methods can be taken and combined. One of the used methods is the scenario technique. Scenarios in general regard the description of a possible situation in the future, based on a complex net of impact factors, as well as the display of a development which could lead to this situation in the future with regard to the present. This method is used for creating surrounding field scenarios, which are defined as the consideration of scenarios with external and unalterable factors [8]. This method is combined with the value benefit analysis, which is used for the analysis of complex alternatives for action [9] due to its adaptability. Additionally some aspects of the method of technology scenarios, which already builds onto the morphological analysis, and the structural approach of TRIZ to collect and store technologies are used for the development of the method for finding sustainable technology pathways [5].

3. Theoretical background of the method

The leading question for developing the method is: how can demands be identified and fulfilled with sustainable systems and how can technologies be applied in systems to promote the reasonably demanded sustainability? The first step on the way to design and implement such technological systems is to develop conceptual solutions which then can be further specified. To fulfil the goal of creating such concepts the developed method consists of four basic elements, which are illustrated in Fig. 1: surrounding field scenarios, the technology pool, screening and system creation [5]. The method can be applied in three different pathways, to answer the raised research question. While the problem induced path is giving answers to the first part of the question, the technology induced path starting from the system and the technology induced path starting from the system element are giving answers to the second part. In the framework of this paper the problem induced path is described in detail and is applied in example used in chapter 4.

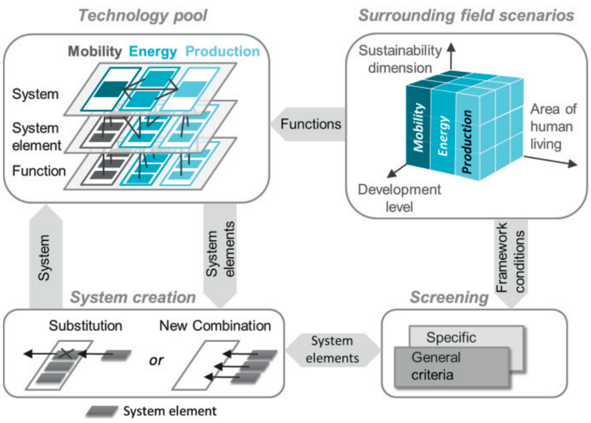

Fig. 1. Overview of the method.

3.1. Elements

Surrounding field scenarios are classified in the three selected areas of human living, mobility, energy and production. They can be applied in three development levels, low, medium and high, and cover the three sustainability dimensions economic, ecological and social. The surrounding field scenarios are the basis to derive functions and the framework conditions used in the screening.

To collect and secure technological knowledge, technologies are stored as system elements and systems in the areas of human living - mobility, energy and production - in a three level model in the technology pool. A system element is defined as an artefact in which technologies are realized. A system is the combination of multiple system elements. At the same time each system can be considered as a system element of a system at a higher level. The corresponding technologies of the system elements are described by their functions. The function, as a neutral description, is later used for substitution or new combination of system elements.

System elements are screened within the superior system. Screening describes the process of a simplified assessment of the system elements. General and specific criteria are used for the screening process. General criteria are used scenario independent, whereas the scenario-specific criteria are derived from the corresponding surrounding field scenarios and can differ depending on the surrounding field scenario.

Coming to the system creation, one result of the screening is a specific amount of problematic system elements within a system. Problematic system elements can be substituted with alternative system elements of the technology pool, which perform the specific function. In the case of a very high number of problematic system elements or a non-existing system, a new system can be created. In a morphological analysis the consistency between all system elements is considered and combined with a pareto optima evaluation regarding the sustainability rating of each system element to create technologicaly consistent and sustainable systems regarding all three sustainability dimensions.

Three pathways are connecting the four elements of the method to either start with an existing system or system element or with a problem for which a sustainable solution is to be found. As in the framework of this paper an exemplary application of the problem induced path is presented, this path is described in detail in the following.

3.2. Problem induced path

The problem induced pathway emanates from the surrounding field scenarios. Out of a single or even a group of surrounding field scenarios first areas of application and then concrete cases of application are identified. On the basis of an identified field of application, the corresponding functions are derived. At the same time the surrounding field scenarios are the source of framework conditions, influencing the specific criteria of the sustainability screening.

In the next step the technology pool is searched for system or system elements, which can fulfill the identified functions. In the screening process the system elements are analyzed and rated with general and scenario-specific criteria. System elements with a too low sustainability score are replaced with system elements of the technology pool, which are suited to perform the same functions, and screened iteratively until a sufficient sustainability score is reached. If the score of all resulting systems is not satisfactory, a new combination is started. In the new combination the consistency between the system elements and their evaluation in the sustainability screening is taken into account to generate pareto-optimal combinations of system elements, in terms of the three sustainability dimensions, with a software tool.

As a final point, the new system is stored in the technology pool. The application of this method is presented in the following chapter and illustrated with a special case of bicycle mobility in Berlin.

4. Application of the method

The method provides the possibility to approach the problem of using sustainable technologies regarding the specific level of development in a country or region as well as different areas of human living. In the framework of the research there has already been generated a variety of applications. Several technologies, which are developed within the Collaborative Research Center (CRC) 1026 – Sustainable Manufacturing, have been transferred into useful applications in the technology induced path. The method has already been applied to low, medium and high development levels in the area of human living production. In this area systems for modular machine tool frames, cacao mass production, the so called living factory as well as adaptronic components for machine tool frames have been created. The exemplary application in case of the system for micro gas turbine production can be classified as part of the areas of human living energy as well as production. Moreover the system of autarkic energy supply in Sierra Leone has been generated as example of a low development level. Both medium and high development levels have been covered by a variety of exemplary applications in the area of mobility with a system for hydrogen mobility, passenger services in São Paulo as well as the in this paper presented applications – which are displayed in Fig. 2 under number 5 and 6. For all applications exist corresponding surrounding field scenarios. These were either created by the authors themselves or adopted from literature.

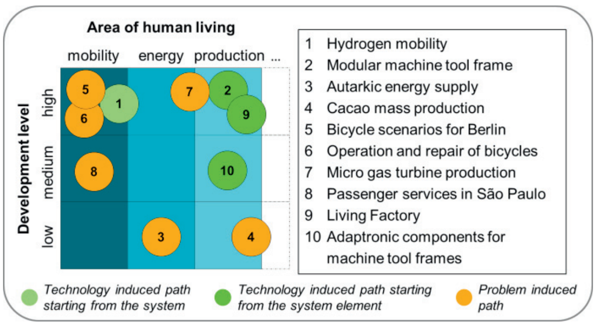

Fig. 2. Overview of the exemplary applications.

4.1. City oriented surrounding field scenarios for bicycle mobility in Berlin

The surrounding field scenarios are the basis for the identification of different systems for bicycle design, operation and repair. The presented surrounding field scenarios have been created to represent different futures with corresponding needs and developments within the city of Berlin regarding mobility.

On the basis of identified key factors with different projections, three surrounding field scenarios have been created. The distinct scenarios, which are illustrated in Fig. 3, show a very positive future of Berlin, a future with an overwhelming recession as well as a future characterized by economic stagnation.

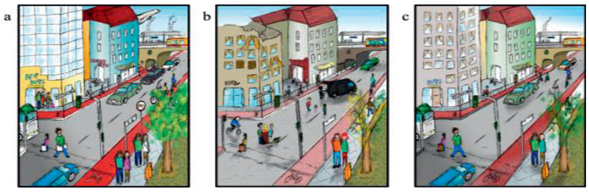

Fig. 3. (a) scenario 1 "Economy on bicycles"; (b) scenario 2 "Wild east"; (c) scenario 3 "Business as usual".

Scenario 1, "Economy on bicycles", describes a very favourable overall development. The economy is growing and the bicycle share in the modal split is increasing. Bicycle usage significantly gains in importance. Bicycles are mainly used for recreational purposes. New technologies and trends are adopted and society is coined by a general climate of health consciousness. Prices for gasoline and public transportation are rising, while the crime rate, especially for bicycle theft, is decreasing.

Scenario 2, "Wild east", on the other hand, describes a scenario with an overwhelming recession. Still, the bicycle share in the modal split is growing notably but with a different reason than in scenario 1. Nevertheless the few public investments made are mainly focusing on public transportation and not on the bicycle infrastructure. Bicycles are used as a cheap mean for transportation for all kinds of goods. The rate of bicycle thievery is increasing.

Scenario 3, "Business as usual", is characterized by economic stagnation. The share of bicycles in the modal split is decreasing and technological innovations for bicycles play a minor role. Even though the bicycle infrastructure is slightly enlarged, bicycles are mainly used for recreational purposes. Prices for gasoline, as well as the rate of bicycle thievery are decreasing.

4.2. Systems for bicycle design, operation and repair

To create different systems for bicycle design, operation and repair general functions of the overall system are identified and corresponding system elements, which are suited to perform these functions, are researched. The system elements are rated with general as well as scenario-specific economic, ecological and social criteria. The general screening criteria are adapted with regards to the described framework conditions in the surrounding field scenarios, leading to a change in weighting for some existing criteria and adding additional criteria.

4.2.1. Creation of systems for bicycle design

In this example the developed method is applied by using the problem induced path to find sustainable solutions for the future mobility with bicycles.

Specific criteria are derived from the surrounding field scenarios with regard to the described framework conditions in the surrounding field scenarios, leading to a change in weighting for some existing criteria and adding additional criteria, as shown in Fig. 4.

		Scenario 1	Scenario 2	Scenario 3
Economic criteria 50%	Total Cost of Ownership	0,5	2	1
	Reliability	1	2	1
	Flexibility	1	2	1,5
	Efficiency	1	1	1
	Energy consumption	2	0,5	1
	Integration into transportation system	2	2	0,5
	Integration into public transportation	2	1	0,5
	Transportation capacity for goods	1	2	0,5
Ecological criteria 25%	Greenhouse gas emissions	2	0,5	1
	Recycling	2	0,5	1
	Consumption of resources	1,5	2	1
	Pollutant emissions	2	0,5	1
Social criteria 25%	*Ergonomics / comfort*	1,5	0,5	1
	Protection from theft	0,5	2	1
	Individualization	2	0,5	2
	Ease of use	2	0,5	1,5
	Endangerment	2	1	2

Underlined	Additional Criteria
0,5	Half weighting of the criteria
1	Simple weighting of the criteria
1,5	One and a half weighting of the criteria
2	Double weighting of the criteria

Fig. 4. System for bicycle design: specific and general criteria.

In the next step the neutral functions of the system as well as corresponding system elements, which are suited to perform these functions, are identified. For example one system element fulfilling the function "energy storage" is the lead accumulator or the lithium-ion accumulator. The complete list of system elements and corresponding functions is displayed in Fig. 5.

Functions	System elements	
Storage of energy	None	1.A
	Li-ion accumulator	1.B
	Flywheel	1.C
	Double layer capacitor	1.D
Carrying (construction)	Diamond frame	2.A
	Mixed form	2.B
	No top frame	2.C
	Compact/unisex	2.D
	Cantilever	2.E
	Integral construction concept	2.F
Carrying (material)	Steel	3.A
	Aluminium	3.B
	Carbon	3.C
	Bamboo	3.D
Transformation 1 (energy generation)	None	4.A
	Solar panels	4.B
Transformation 2 (energy recuperation)	None	5.A
	KERS	5.B
	Shock absorption	5.C
Transformation 3 (gearshift)	None	6.A
	Derailleur gear	6.B
	Hub gears	6.C
	PINION bottom bracket gear box	6.D
	CVT	6.E
	Automatic	6.F

Functions	System elements	
Transformation 4 (additional propulsion)	None	7.A
	Electric motor	7.B
	Additional pedal-powered	7.C
	Speedway	7.D
Carrying 1 (passenger-transport)	None (no second seat)	8.A
	Additional seat	8.B
Carrying 2 (carriage of goods)	None	9.A
	Additional storage space	9.B
Locate/ transport data	GPS-reciever	10.A
	Radio	10.B
	WLAN	10.C
Provision of information (on-board-computer)	None	11.A
	Cyclocomputer	11.B
	Mobile interface and application	11.C
Authentication (lock)	None	12.A
	Card/chip	12.B
	Key	12.C
	Wireless	12.D

Fig. 5. System for bicycle design: functions and system elements.

The specific criteria are applied to rate these system elements. Additionally the dependencies of the system elements are evaluated with a consistency matrix, which is exemplarily illustrated in Fig. 6. The consistency between two system elements is rated on a scale from 1 to 5. 1 describes a total inconsistency, 5 a high consistency and 3 independence of two system elements.

For example "no energy recuperation" has a high consistency with "no energy storage". But if energy is recuperated, there is a need for some kind of energy storage, so there is a total inconsistency between "kinetic energy recuperation system" and "no energy storage".

Consistency matrix — Valuation standard: 1 = Total inconsistency; 5 = Strong mutual support / high consistency

Function		System element	Energy storage: 3A None	3B Li-Ion accumulator	3C Fly Wheel	3D Double layer capacitor	...	Energy recuperation: 6A None	6B Kinetic Energy Recuperation (electric)	6C Shock absorber
Energy storage	3A	None								
Energy storage	3B	Li-Ion accumulator								
Energy storage	3C	Fly Wheel								
Energy storage	3D	Double layer capacitor								
Energy storage	...	...								
Energy recuperation	6A	None	5	3	3	3	..			
Energy recuperation	6B	Kinetic Energy Recuperation System (KERS)	1	4	4	5	..			
Energy recuperation	6C	Shock absorber	1	5	4	5	..			

Fig. 6. System for bicycle design: Consistency matrix.

4.2.2. Created systems for bicycle design

In the first application, consistent systems for bicycle design are developed within the problem induced path. Each bicycle is expanded by functions corresponding to each surrounding field scenario.

The importance of each criterion differs with the surrounding field scenario. For example the wealth in the first scenario "Economy on bicycles" implies higher weighted ecological criteria in comparison to the economic criterion "Total Cost of Ownership". In the second scenario "Wild east" the economic criteria and in the third scenario "Business as usual" individuality are weighted comparatively high.

Taking into account the consistency evaluation of all system elements and the result from the sustainability screening, pareto optimal system element combinations can be found for each consistency level. The shown results of the system creation describe a balance between consistency and sustainability score for the surrounding field for each scenario. They are as well close to the theoretical maximum for consistency as well as for sustainability. In Fig. 7 the three results of the system creation for bicycle design are illustrated.

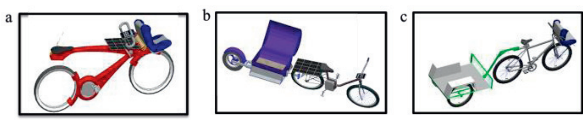

Fig. 7. (a) system 1; (b) system 2; (c) system 3.

To meet the requirements of the first scenario, the resulting bicycle is realized with integral construction and lighter weight. There is an extra seat in front to support increased mobility, recreational use and individualization. A lithium-ion accumulator integrated in the steel frame enhances the mobility of the user especially in case of an additional passenger in the front seat. Energy recuperation with a shock absorber as well as energy generation with solar cells improve energy efficiency and the range of bicycles. Moreover many high tech solutions including an electric motor and wireless communication devices are combined in system 1.

On the other hand the design in system 2 is simpler and focusing on the transportation of goods, since bicycles replace some of the transportation tasks formerly done with other vehicles, due to the lower cost of bicycles. The design number 3 is rather simple as well and characterized by the use for recreation. The easy detachable trailer, for example, can be used to transport sporting goods.

4.2.3. Systems for bicycle operation and repair

This application also follows the problem induced path by identifying sustainable solutions for the operation and repair of bicycles and thereby integrating technologies developed within the CRC 1026 into a sustainable system. There is a need for operation and repair of bicycles in all 3 surrounding field scenarios. The configuration of the operation and repair system has to be adapted to the framework conditions. Some of the integrated technologies are described shortly in the following section.

In general, a "learnstrument" is an artefact which automatically demonstrates its functionality to the user [10]. The self-help workplace learnstrument combines simple assembly technologies and tools with multimedia or internet based training material. Non-commercial workshops provide material infrastructure while instructional material is developed and distributed by a community of interested stakeholders.

The industrial workplace learnstrument combines image-based tracking systems and professional work systems with expert software for task classification and assessment. This provides an effective and efficient means for automated generation of training and feedback material [11].

The third technology consists of sensors for condition monitoring of bicycles to automatically detect critical parameters. Such sensors have the ability to communicate e.g. via Bluetooth and other telecommunication technologies with other sensors. They can be integrated into a maintenance, repair and overhaul system.

Fig. 8 illustrates the created system "Do it yourself service" for the described surrounding field scenarios 2 and 3, "Wild east" and "Business as usual". In this system a widespread bike rental system is used, in which sensors provide the possibility to locate and reserve a bicycle near the user. At the same time the sensors monitor the condition of the bicycle. If the bicycle needs to be repaired (corrective or preventive), the user of the bicycle is informed about this task and can fix the bicycle herself in a nearby "do it yourself workshop".

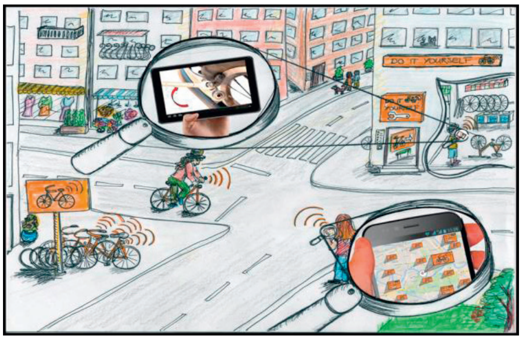

Fig. 8. Created system "Do it yourself service" for the surrounding field scenarios 2 and 3, "Wild east" and "Business as usual".

At the workshop the user is guided through the specific repair tasks by a system to use the necessary tools which are provided. At the same time the user is provided with all the necessary information to fulfill even advanced tasks. This is possible since this information is provided by an interactive learning system.

As an incentive to fulfill these repair tasks the user receives free time to use bikes out of the rental pool without charge. The free time added to the balance of the users bike rental account depends on the type of repair task fulfilled.

5. Conclusion and outlook

The generated systems for bicycle mobility in Berlin show the high dependency of future development of technology as well as operating systems of different factors which are taken into account within the specific criteria. These criteria are directly influenced by the surrounding field scenarios. The developed and presented method represents a possibility to integrate this aspect as well as different development levels.

While there are some similarities between the created systems it is clearly demonstrated that for some developments of the surrounding field rather different technologies for mobility are required to achieve sustainable solutions.

In a next step additional scenarios could be created for the bicycle mobility in other countries. A high impact could especially be achieved in emerging countries with a high potential for a broader use of these sustainable means of transportation. One specific country of interest could be Vietnam in South-East-Asia.

As illustrated in Fig. 2 in the mobility area of human living on a low development level and in the energy area of human living on a medium development level, the method has not been applied yet. In addition to the at least partially tackled areas of human living production, mobility and energy the application of the method could also be broadened to other areas like housing and health.

Regarding the method itself there is still potential for further development. To allow the realization of breakthrough innovations, for which not even the combination of functions is yet known, prior to the already implemented system element combination a combination of functions itself could be carried out. This would allow adding new features to an already known system as for example experienced with the transformation from the regular cellphone to so called smartphones like the iPhone which includes multiple additional functions. While the sustainability screening is clearly differentiated from an in detail sustainability evaluation, the quality of information and uncertainty regarding the screening could be taken into account to make this factor visible and put further emphasis on improving it [5]. Finally to speed up the process of transferring and/or adapting systems to different surrounding fields a country classification regarding the different areas of human living could be helpful.

The method can be a useful tool not only for researchers depicting sustainable pathways of technology development, but also for industry to exploit new fields of application for long term steering of their product strategy and their research and development activities, for governmental institutions to create the right environment for sustainable innovation by policy changes as well as for individuals to find suitable applications for technology innovations.

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