



NET PRESENT VALUE EVALUATION OF ENERGY PRODUCTION AND CONSUMPTION IN REPEATED REVERSE LOGISTICS

Danijel KOVAČIČ^a, Marija BOGATAJ^b

^aDK-Informacijsko svetovanje, Grič 4, SI-1000 Ljubljana, Slovenia

^bMEDIFAS, Mednarodni prehod 6, Vrtojba SI-5290, Šempeter pri Gorici, Slovenia

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Abstract. The paper is based on Grubbström's MRP theory previously used in analysis of production processes "under one roof". This theory has recently been extended to model global supply chains by Bogataj and Grubbström, both scientists from the MEDIFAS faculty. Every production cycle is followed by distribution, consumption and recycling activities. In broad supply chains, transportation costs between pairs of activity cells have a significant impact on the overall net present value of the system. Possible flows inside or between subsystems can all be described with input-output matrices H and G . Recently published papers of the above mentioned authors describe the presentation of supply chains in a generalized form. Generalized input and output matrices $\mathbf{H}(s)$ and $\mathbf{G}(s)$ hold technical coefficients and lead times. Lead times are split into 2 parts: production and transportation. As presented in the publication of R. W. Grubbström, L. Bogataj and M. Bogataj, and further research of these authors, the results of recycling activities in the extended MRP model are the recovered and the waste items, but in their model the recycling of the items is not repeated.

Recovered items could be reused several times in future production cycles, reducing the need to purchase new items on the market as considered here. The waste items must be disposed of, requiring environmental taxes which vary among regions, depending on local environmental policy. If recovered, items must be delivered from the recycling facility back to production, and waste items must be sent to landfills. This process requires an expenditure of human resources, and energy at each activity cell plays an important role. In this article we show how the location of recycling facilities, the prices and quantity of energy needed and the environmental taxes can drastically influence the net present value for the entire system. We also present the method for evaluating cases where energy can be recovered during recycling or decomposition processes at landfills. It is also assumed that energy recovery can be stimulated with subsidized purchase prices, but generally, lower quality energy can be expected as an output of these processes. This paper introduces generalized input and output energy matrices, which describe these energy flows and their impact on environmental sustainability through the net present value of the system, which is the novelty in the extended MRP theory.

Keywords: energy, extended MRP theory, reverse logistics, supply chain, location, land use, net present value.

JEL Classification: C6, Q4, Q5, R15, R32, R51, R53.

Corresponding author Marija Bogataj
E-mail: marija.bogataj@guest.arnes.si

Introduction

MRP theory has been widely researched and improved upon over the last quarter of a century. This theory is a scientific approach to the well-known Material Requirements Planning (MRP), which has been implemented for several decades. MRP has enjoyed economic success in several economic systems, and Orlicky (1975) provided inspiration for scientific observation. Though MRP systems are widely used in manufacturing companies, they exhibit significant drawbacks (D'Avino *et al.* 2014). For example, these authors developed Rev MRP algorithm in order to reduce the system nervousness, generate a more regular pattern of order released and lower inventory levels. But the general theory on MRP has been developed by Grubbström and other researchers gathered around MEDIFAS. While in majority of papers cost approach is used (Zeballos *et al.* 2014; Rappold, Yoho 2014), Net Present Value (NPV) approach developed by Grubbström enable a broader study of equilibrium for Economy – Energy – Environment. Many works by Grubbström *et al.* show that MRP is not only usable practically, but it is also a good basis for deeper scientific research of macroeconomic problems – even environmental issues. In recent paper (Grubbström, Tang 2012), which follows up the former paper of Grubbström *et al.* (2010) and Grubbström (2012), the authors also investigate the complexity defined as the number of possible feasible solutions (production plans). They show how properties of external demand, timing and properties of requirements (Bill-of-Materials) have consequences on the rapidly growing size of the solution space.

Basic MRP theory addresses multistage, multiperiod production and inventory systems. Multistage assembly systems of MRP are usually graphically presented with a Bill of Materials (BOM). A BOM shows the structure of the product as a tree. This structure can be presented in a more compact network description using Gozinto graphs (Vazsonyi 1958). The MRP assembly system can also be conveniently written using Leontief (1928) input-output matrices. Grubbström, Lundquist (1989) stated that, “[The] Input-Output Analysis model presents the opportunity to transform one set of resources into another set using an efficient mathematical language”. This fact places input-output analysis as one of the main pillars of this theory.

In addition to input-output analysis, another important pillar of MRP theory is lead time. Adding timing properties to the physical structure of the elements in the system allows us to observe the complete structure of the product. The incorporation of lead times into MRP theory has been accomplished by using Laplace transform (Grubbström, Molinder 1994; Grubbström, Ovrin 1992). These studies are based on the work of Grubbström (1967), where he explained how to use Laplace transform to solve different economic problems.

When we replace the frequency s by continuous interest rate ρ Laplace transform can be used to observe cash flows when calculating the net present value (NPV), which is the third important ingredient of the MRP theory (Grubbström 1998):

$$\text{NPV} = \int_0^{\infty} a(t)e^{-\rho t} dt = \tilde{a}(\rho), \quad (1)$$

which is a NPV of cash flow $a(t)$.

A good overview of the details of basic MRP theory and the inspiration for its development can be found in Grubbström, Tang (2000). These developments have been generally connected to production-inventory systems.

MRP theory can be extended in such way that it also provides answers to macroeconomic problems. This extension was first presented by Grubbström *et al.* (2007). They extended multistage assembly systems with 3 additional subsystems: (2) distribution, (3) consumption and (4) recycling, as shown in Figure 1. This extension has been further elaborated in papers of Bogataj, Grubbström (2012, 2013) and the influence of aging on timing in such systems has been evaluated in Bogataj *et al.* (2013) while implementation in food industry is presented in Kovačić *et al.* (2015).

Figure 1 presents a closed system where produced elements are distributed to consumption activity cells, where they enter recycling at the end of their lifecycle. Environmental taxes as an integral part of pricing in the system are introduced. Return rates of recovered used elements depend on this taxation. It also shows how local legislation could stimulate reuse instead of disposal and new purchases. Extension to complete supply chain, which also covers environmental and spatial aspects, is called the extended MRP theory. After the introduction of lead times in production matrix and separately in transportation matrix, generalized input and output matrices $\check{H}(s)$ and $\check{G}(s)$ of such systems, which consist of both technical coefficients and lead times, are:

$$\check{H}(s) = \begin{bmatrix} \check{H}_{11}(s) & \check{H}_{12}(s) & 0 & \check{H}_{14}(s) \\ 0 & 0 & \check{H}_{23}(s) & \check{H}_{24}(s) \\ 0 & 0 & 0 & \check{H}_{34}(s) \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad \check{G}(s) = \begin{bmatrix} \check{G}_{11}(s) & 0 & 0 & \check{G}_{14}(s) \\ 0 & \check{G}_{22}(s) & 0 & 0 \\ 0 & 0 & \check{G}_{33}(s) & 0 \\ 0 & 0 & 0 & \check{G}_{44}(s) \end{bmatrix}. \quad (2)$$

Matrix $\check{H}(s)$ consists of 16 sub-matrices $\check{H}_{ij}(s)$, in which some are positive and some equal zero. Zero sub-matrices mean that no inflows into the corresponding subsystem appear. Individual sub-matrix $\check{H}_{ij}(s)$ relates to items that are required by subsystem i due to the processes in subsystem j . Similar assumptions can be made for sub-matrix $\check{G}_{ij}(s)$, which relates to the outputs of subsystem i as requirements for the processes in subsystem j . Sub-matrix $\check{G}_{ij}(s)$ coincides with $\check{H}_{ij}(s)$ in dimension.

As explained in Grubbström, Tang (2000), after frequency s is replaced with ρ , the NPV of the system can be calculated using generalized input and output matrices $\check{H}(\rho)$ and $\check{G}(\rho)$:

$$NPV = \mathbf{p}(\check{G}(\rho) - \check{H}(\rho))\check{P}(\rho) - \hat{\mathbf{K}}\check{\mathbf{v}}(\rho), \quad (3)$$

where \mathbf{p} is a price vector holding the prices of elements at any state of the system. The prices of recycling subsystem (p_k^4) are environmentally important because they correspond to environmental taxation. These prices will usually be negative because the disposal of waste elements cannot be performed without payment for the environmental damage caused. Furthermore, $\check{P}(\rho)$ presents the production plan, $\check{\mathbf{v}}(\rho)$ is the given timing and $\hat{\mathbf{K}}$ is the vector of setup costs, which are well-known parameters of basic MRP theory (the reader is encouraged to refer to the papers mentioned above for detailed descriptions and discussions of these parameters).

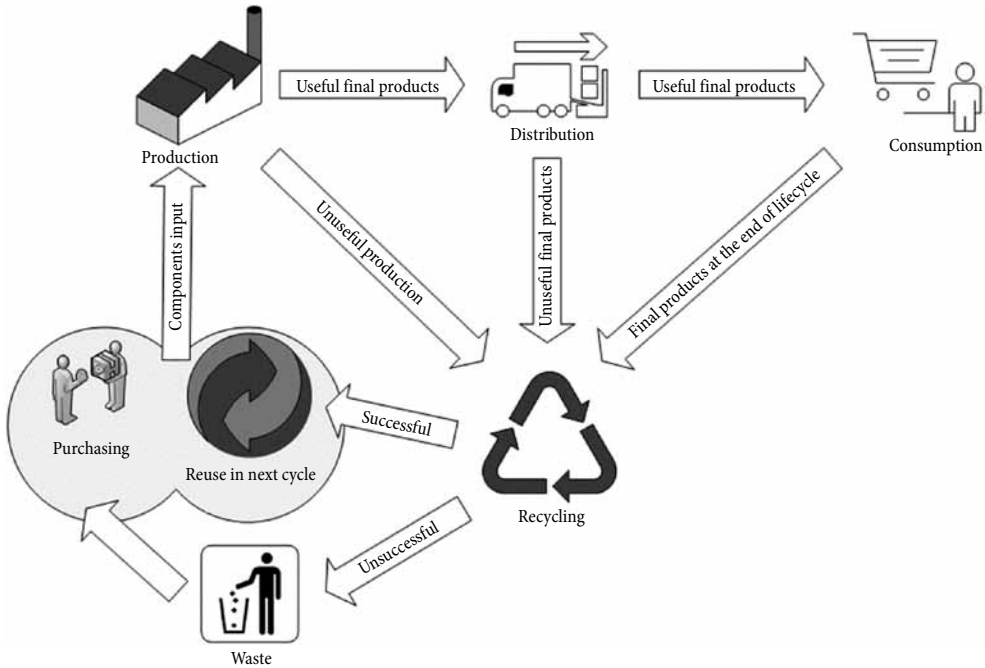


Fig. 1. Presentation of the cyclical extended MRP theory model with 4 subsystems

Application of the extension of MRP theory to the entire supply chain forced researchers to think about lead times as a result of transportation activities. Traditional MRP theory dealt only with production lead times. This approach was sufficient for assembly processes where all components of a certain assembly level had to be in place $t - \tau$ time units before completion and where t is the time of completion. This assumption is valid strictly for only assembly processes where all activities are performed inside one location of activity cells. As soon as we look more broadly, and when we allow processes to be performed in several geographically dispersed activity cells, it is necessary to consider transportation lead times. Lead times can be unique for each individual pair of activity cells where transportation flow appears. The necessity for inclusion of transportation lead times in extended MRP theory is well presented by Bogataj, Grubbström (2012). Transportation costs influence the total NPV of the system and should be an integral part of the calculation. Transportation costs per unit are covered under matrices $\tilde{\Pi}_H(\rho)$ and $\tilde{\Pi}_G^{14}(\rho)$, which were introduced by Bogataj, Grubbström (2013). They denote transportation costs as:

$$NPV_{\text{transportation}} = -\mathbf{U}^T (\tilde{\Pi}_G(\rho) + \tilde{\Pi}_H(\rho)) \tilde{\mathbf{P}}(\rho), \tag{4}$$

where \mathbf{U}^T is row vector of unit values and $\tilde{\mathbf{P}}(\rho)$ is a production plan. Transportation lead times and costs consequently determine the attractiveness of the individual activity cell, which was presented by Bogataj *et al.* (2011). This study clearly shows how one activity cell can be replaced with another, which would lead to better systems performance (measured

by higher NPV). It is clearly shown that MRP theory is an appropriate tool for the evaluation of geographical factors and their contributions to the profitability of the system.

The cyclical model of the 4 subsystems was further developed by Kovačić, Bogataj (2011). This work denotes input and output matrices for the 4 subsystems \mathbf{H} and \mathbf{G} in general form and includes all possible material flows in the system. This study shows that it is possible to track every element in the system through several cycles until this element ends as a waste element at the landfill.

Kovačić, Bogataj (2013) were the first to present energy as an input into the system. This inclusion merely focuses on the impact of energy on the behavior of the return rates of used elements, which are covered under technology coefficients of generalized output matrix $\tilde{\mathbf{G}}(\rho)$.

This paper further analyzes the impact of energy on the system as a whole. Energy demands appear inside each individual activity cell. This energy can, in some cases, be physically distributed to the activity cell (*i.e.*, fuel or coal), or it may be available through the distribution network immediately at the needed time (*i.e.*, electricity). Modern technology allows us to “recycle” energy: it can appear as a by-product of reverse logistics or as a result of decomposition of waste material in the landfill. In this last case, additional decomposition lead times should be considered in the model. Outputs and inputs of energy will be evaluated through NPV. Therefore, generalized input and output energy matrices $\tilde{\mathbf{E}}_H(\rho)$ and $\tilde{\mathbf{E}}_G(\rho)$ will be introduced. It is assumed that the quantity and quality of recovered energy are typically lower than energy input demands. It will be shown that for this reason subsidizing the recovery is necessary for stimulating energy reuse because, from economic perspective, other sources of energy could be cheaper if environmental policy does not support the internalization of environmental damages.

1. Energy in extended MRP theory

The increase in population and greater technological development drastically changed energy requirements. It is estimated that 70% of the world energy consumption could be provided from renewable resources by the year 2050 (Ertay *et al.* 2013). The increase in energy demand influences the air quality and the overall pollution of the planet greatly. Lich, Tournemaine (2013) show how pollution influence allocation of residents and activities which also need to be evaluated in study of economic and environmental equilibrium. Using the environmental Kuznets curve (Lapinskiene *et al.* 2014) show that when a certain level of income per capita is reached, further economic growth leads to improvement of the environment. This paper is a step to study of such improvement.

Higher prices and limited resources are stimulating new approaches to energy production. Long-term sustainability forces us to think about so-called green and renewable energy. These changes are stimulating researchers, and consequently, many recent works focus on energy use and pollution. Albino *et al.* (2003) use input-output analysis as a tool for describing material and energy flows, pollution and waste. They point to production and energy recovery as important ingredients of the system and for environmental sustainability.

From the point of the global supply chain, energy is needed inside each activity cell; it is crucial during all phases of the production process and is needed for physical distribution from one activity cell to another. Many final products also use energy during their lifecycle (e.g., electronic devices and cars). At the end of the supply chain, recycling activities usually require high energy inputs in order to disassemble elements to their components. Energy costs of disassembly may greatly affect optimal return rates of recycled components back to production. On the other hand, recycling activities could, in some cases, be a source of renewable energy. To stimulate investment in expensive infrastructure for the reverse production of energy, the purchase price of energy may need to be subsidized by the authorities. On the other hand, sometimes this renewable energy can also be used directly for running recycling activities.

Figure 2 denotes the described model for the example of one recycling activity cell. The batch of used elements P_i enters the recycling facility. Sufficient quantities of labor force L and energy E are needed to finalize each activity (recycling the batch of input elements P_i). The results of the recycling activities can be divided into 3 categories:

- 1) components P_j, P_k, \dots, P_n of the element P_i , which were successfully recycled and can be reused in the next production cycle,
- 2) waste elements W_j, W_k, \dots, W_n , which were not recycled and finish their cycle in the landfills,
- 3) recovered energy E_j, E_k, \dots, E_n as a by-product of recycling or decomposing of individual elements j, k, \dots, n .

The NPV of one cycle of the complete supply chain consisting also of energy and labor force costs can be calculated as:

$$NPV = \mathbf{p} \left(\tilde{\mathbf{G}}(\rho) - \tilde{\mathbf{H}}(\rho) \right) \tilde{\mathbf{P}}(\rho) - \hat{\mathbf{K}} \tilde{\mathbf{v}}(\rho) - \mathbf{U}^T \left(\tilde{\mathbf{\Pi}}_G(\rho) + \tilde{\mathbf{\Pi}}_H(\rho) \right) \tilde{\mathbf{P}}(\rho) - \mathbf{c}_L \hat{\mathbf{L}} \tilde{\mathbf{v}}(\rho) - \mathbf{U}^T \left(\tilde{\mathbf{E}}_H(\rho) - \tilde{\mathbf{E}}_G(\rho) \right) \tilde{\mathbf{P}}(\rho). \tag{5}$$

Here, $\mathbf{c}_L \hat{\mathbf{L}} \tilde{\mathbf{v}}(\rho)$ denotes the NPV of the labor force, and $\mathbf{U}^T \left(\tilde{\mathbf{E}}_H(\rho) - \tilde{\mathbf{E}}_G(\rho) \right) \tilde{\mathbf{P}}(\rho)$ denotes the NPV of energy costs. Energy will be treated individually for each activity cell, which means that generalized input and output energy matrices $\tilde{\mathbf{E}}_H(\rho)$ and $\tilde{\mathbf{E}}_G(\rho)$ will coincide in dimension with generalized input and output matrices $\tilde{\mathbf{H}}(\rho)$ and $\tilde{\mathbf{G}}(\rho)$. Further, \mathbf{U}^T is a row vector of unit values, \mathbf{c}_L is the price of the labor force and $\hat{\mathbf{L}} \tilde{\mathbf{v}}(\rho) = \tilde{\mathbf{L}}(\rho)$ is the working plan of recycling activities.

Figure 3 denotes energy as an input to the production subsystem on the lowest level of 2 adjacent activity cells i and j . During this assembly process, h_{ij}^{11} units of component i are needed for the assembly of one unit of element j . To finalize this transformation, E_{ij}^{11} units of energy are needed as an input for every component i .

In many cases, we can expect disassembly activities to be quite energy-consuming. Figure 4 shows energy as an input and output of the disassembly process.

Element j can enter recycling from any of the 3 other previous subsystems. The results of its disassembly are g_{ji}^{14} units of recycled components i , which can be reused in the next production cycle, and g_{ji}^{44} units of waste components i , which must be disposed of and finish their cycle in landfills. Disassembly of 1 unit of element j requires E_{ji}^{14} , E_{ji}^{24} or E_{ji}^{34} units of energy, depending on the output subsystem of element j .

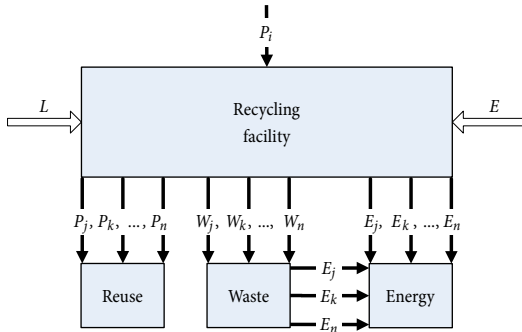


Fig. 2. Inputs needed for disassembly process and its outputs: recycled and waste elements and energy

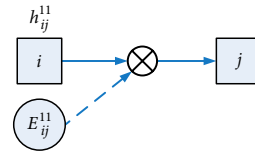


Fig. 3. Two activity cells of production subsystem where h_{ij}^{11} units of element i and E_{ij}^{11} units of energy per element i are needed for the assembly of one unit of element j

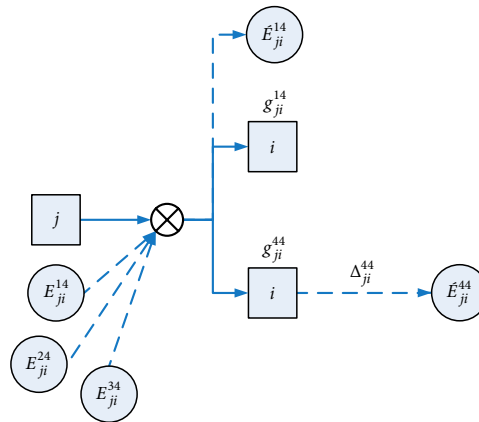


Fig. 4. Disassembly of one unit of input element j to recycled and waste quantities g_{ji}^{14} and g_{ji}^{44} of element i , where E_{ji}^{14} , E_{ji}^{24} , E_{ji}^{34} are input and E_{ji}^{14} , E_{ji}^{44} are output quantities of energy

During the disassembly processes of element j , some energy might be recovered. The output quantity of the energy is denoted as \dot{E}_{ji}^{14} , and it appears at the end of the process. Additionally, some energy might also be recovered later from waste elements, which ended their lifecycle in the landfill (*i.e.*, the known practice of energy production from gas, which results from the decomposition of waste in the landfills). Recovered energy, which is a result of the decomposition of un-recycled components of 1 unit of element j , is denoted as \dot{E}_{ji}^{44} . This energy will appear with some additional lead time Δ_E^{44} after the recycling activities end and after the transportation of waste to landfills at time t .

In practice, we can expect output energy to be in a lower quality form compared to what the system requires as an input. In typical supply chains, potential energy, which is an input required to finish the activities inside all 4 sub-systems, is usually transformed into kinetic energy. On the other hand, recycling and decomposition processes will usually provide outputs in the form of thermal energy. Recovered energy in the form of heat is very difficult to transform into other forms of energy. Its transportation possibilities are also

limited. The result of these physical constraints is that the value of 1 unit of output energy is lower than the input energy, which is easier to transport and transform. The recovery of energy will also increase setup costs inside the activity cell, which will consequently decrease the overall NPV of the system. Decrease of the NPV could make recovery of the energy economically unattractive from a micro point of view at the individual activity cell level. However, from a global perspective such processes are necessary for long-term environmental sustainability and the availability of resources. The responsibility of the policy-makers is to stimulate reuse of all resources, including energy, if this could improve the sustainability of environment. Only the policy-makers on local, regional, national and EU level can introduce measures to create incentives to motivate the users to maintain long-term sustainability of the environment. These incentives are also one of the main topics of H2020. As stated in “A strategy for smart, sustainable and inclusive growth” (European Commission 2010: 3): “The Commission is putting forward seven flagship initiatives to catalyse progress under each priority theme:”, including “Resource efficient Europe” to help decouple economic growth from the use of resources, support the shift towards a low carbon economy, increase the use of renewable energy sources...” This stimulation can be covered with subsidized energy prices or other regulatory mechanisms for determining the fraction of recovered energy (*i.e.*, directives).

Prices of one unit of energy can differ among the individual activity cells. This fact should be considered when determining the structure of generalized input and output energy matrices. The cost of input energy ε_{ij}^H , which is needed at activity cell i , can be denoted as a product of the price of the energy per unit c_{ij}^E and required quantity of the energy E_{ij}^H to transform 1 unit of the component to the higher assembly level:

$$\varepsilon_{ij}^H = c_{ij}^E E_{ij}^H. \quad (6)$$

In a similar manner, the value of output energy ε_{ji}^G , which is a by-product of decomposition of non-recovered components i , can be calculated as:

$$\varepsilon_{ji}^G = p_{ji}^E \acute{E}_{ji}^G. \quad (7)$$

As discussed earlier in this chapter, the sell price of recovered energy p_{ji}^E may vary due to the market price of energy c_{ji}^E for the same activity cell. Policy can effectively stimulate reuse of the energy with differentiation $p_{ji}^E > c_{ji}^E$. The difference between the selling and buying price $p_{ji}^E - c_{ji}^E$ can be interpreted as a subsidy for the long-term environmental sustainability of supply chain.

According to the description above, the generalized input energy matrix $\check{\mathbf{E}}_H(\rho)$ has the same dimension as the generalized input matrix $\check{\mathbf{H}}(\rho)$ and can now be denoted as:

$$\check{\mathbf{E}}_H(\rho) = \begin{bmatrix} \check{\mathbf{E}}_{11}^H(\rho) & 0 & 0 & \check{\mathbf{E}}_{14}^H(\rho) \\ 0 & 0 & 0 & \check{\mathbf{E}}_{24}^H(\rho) \\ 0 & 0 & 0 & \check{\mathbf{E}}_{34}^H(\rho) \\ 0 & 0 & 0 & 0 \end{bmatrix}. \quad (8)$$

Positive sub-matrices appear only inside of those activities where the demand for energy actually exists. These demands are present only inside the production subsystem (sub-matrix $\tilde{\mathbf{E}}_{11}^H(\rho)$) and inside the recycling subsystem (sub-matrices $\tilde{\mathbf{E}}_{14}^H(\rho)$, $\tilde{\mathbf{E}}_{24}^H(\rho)$ in $\tilde{\mathbf{E}}_{34}^H(\rho)$). We assume that the energy requirements of the distribution subsystem are covered by the distribution costs (*i.e.*, fuel needed for transportation). However, it would also be possible to move energy from transportation to the energy matrix. We assume that the final product is consumed at some location, and the energy requirements of the final product during its lifecycle are excluded from the model. On the other hand, the model could be upgraded further in a way to also cover the energy requirements of the final product during its lifecycle. Such an approach would provide us with additional opportunities to study the impact of the energy efficiency of the final products to the overall balance of the system.

Special emphasis should be given to energy lead times. The general structure of the generalized input energy matrix $\tilde{\mathbf{E}}_H(\rho)$ covers transportation and production lead times. Transportation lead times $e^{\rho(\tau_{ij}^H)^{tr}}$ appear in only the case of physical distribution of energy (*e.g.*, gas, fuel, coal). The physical distribution of energy is not always needed (*i.e.*, electricity), and in such cases, transportation lead times will equal 0. The transportation lead times of energy will usually differ from the transportation lead times of the physical elements of the system (raw materials of assembled components).

According to the interpretation described above, individual positive generalized input energy sub-matrices can be written in general form as:

$$\tilde{\mathbf{E}}_{11}^H(\rho) = \tilde{\mathbf{E}}_{11}^{H^{tr}}(\rho) \tilde{\boldsymbol{\tau}}_{11}^{pr}(\rho) =$$

0	0	0	...	0
0	0	0	...	0
$\varepsilon_{31}^{11} h_{31}^{11} e^{\rho(\tau_{31}^1)^{tr}}$	0	$\varepsilon_{33}^{11} h_{33}^{11} e^{\rho(\tau_{33}^1)^{tr}}$	...	$\varepsilon_{3n}^{11} h_{3n}^{11} e^{\rho(\tau_{3n}^1)^{tr}}$
0	0	0	...	0
$\varepsilon_{51}^{11} h_{51}^{11} e^{\rho(\tau_{51}^1)^{tr}}$	$\varepsilon_{52}^{11} h_{52}^{11} e^{\rho(\tau_{52}^1)^{tr}}$	0	...	$\varepsilon_{5n}^{11} h_{5n}^{11} e^{\rho(\tau_{5n}^1)^{tr}}$
0	0	0	...	0
⋮	⋮	⋮	⋮	⋮
$\varepsilon_{(2n-1)1}^{11} h_{(2n-1)1}^{11}$ $e^{\rho(\tau_{(2n-1)1}^1)^{tr}}$	$\varepsilon_{(2n-1)2}^{11} h_{(2n-1)2}^{11}$ $e^{\rho(\tau_{(2n-1)2}^1)^{tr}}$	$\varepsilon_{(2n-1)3}^{11} h_{(2n-1)3}^{11}$ $e^{\rho(\tau_{(2n-1)3}^1)^{tr}}$	...	0
0	0	0	...	0
$\varepsilon_{(2n+1)1}^{11} h_{(2n+1)1}^{11}$ $e^{\rho(\tau_{(2n+1)1}^1)^{tr}}$	$\varepsilon_{(2n+1)2}^{11} h_{(2n+1)2}^{11}$ $e^{\rho(\tau_{(2n+1)2}^1)^{tr}}$	$\varepsilon_{(2n+1)3}^{11} h_{(2n+1)3}^{11}$ $e^{\rho(\tau_{(2n+1)3}^1)^{tr}}$	...	$\varepsilon_{(2n+1)n}^{11} h_{(2n+1)n}^{11}$ $e^{\rho(\tau_{(2n+1)n}^1)^{tr}}$
$\varepsilon_{(2n+2)1}^{11} h_{(2n+2)1}^{11}$ $e^{\rho(\tau_{(2n+2)1}^1)^{tr}}$	$\varepsilon_{(2n+2)2}^{11} h_{(2n+2)2}^{11}$ $e^{\rho(\tau_{(2n+2)2}^1)^{tr}}$	$\varepsilon_{(2n+2)3}^{11} h_{(2n+2)3}^{11}$ $e^{\rho(\tau_{(2n+2)3}^1)^{tr}}$	...	$\varepsilon_{(2n+2)n}^{11} h_{(2n+2)n}^{11}$ $e^{\rho(\tau_{(2n+2)n}^1)^{tr}}$
⋮	⋮	⋮	⋮	⋮
$\varepsilon_{m1}^{11} h_{m1}^{11} e^{\rho(\tau_{m1}^1)^{tr}}$	$\varepsilon_{m2}^{11} h_{m2}^{11} e^{\rho(\tau_{m2}^1)^{tr}}$	$\varepsilon_{m3}^{11} h_{m3}^{11} e^{\rho(\tau_{m3}^1)^{tr}}$	...	$\varepsilon_{mn}^{11} h_{mn}^{11} e^{\rho(\tau_{mn}^1)^{tr}}$

$\left[\begin{array}{ccc} e^{\rho(\tau_1^1)^{pr}} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & e^{\rho(\tau_n^1)^{pr}} \end{array} \right];$

$$\tilde{\mathbf{E}}_{14}^H(\rho) = \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ \varepsilon_{21}^{14} h_{21}^{14} e^{\rho \tau_{21}^{14}} & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ 0 & \varepsilon_{42}^{14} h_{42}^{14} e^{\rho \tau_{42}^{14}} & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & \varepsilon_{63}^{14} h_{63}^{14} e^{\rho \tau_{63}^{14}} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & \varepsilon_{(2n)n}^{14} h_{(2n)n}^{14} e^{\rho \tau_{(2n)n}^{14}} \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix}; \tag{10}$$

$$\tilde{\mathbf{E}}_{24}^H(\rho) = \begin{bmatrix} 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \\ \varepsilon_{(r+1)1}^{24} h_{(r+1)1}^{24} e^{\rho \tau_{(r+1)1}^{24}} & 0 & \dots & 0 \end{bmatrix}; \tag{11}$$

$$\tilde{\mathbf{E}}_{34}^H(\rho) = \begin{bmatrix} \varepsilon_{11}^{34} h_{11}^{34} e^{\rho \tau_{11}^{34}} & 0 & \dots & 0 \end{bmatrix}. \tag{12}$$

Next, generalized output energy matrix $\tilde{\mathbf{E}}_G(\rho)$ can be written in the following form with only 2 positive sub-matrices, which correspond to recycling activities:

$$\tilde{\mathbf{E}}_G(\rho) = \begin{bmatrix} 0 & 0 & 0 & \tilde{\mathbf{E}}_{14}^G(\rho) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \tilde{\mathbf{E}}_{44}^G(\rho) \end{bmatrix}. \tag{13}$$

Energy as an output appears as only a by-product of recycling activities ($\tilde{\mathbf{E}}_{14}^G(\rho)$ and $\tilde{\mathbf{E}}_{44}^G(\rho)$). We can treat such recovered energy as green. The lower quality of recovered energy and the relatively high setup costs can be compensated for with higher purchase prices, which are subsidies for long-term sustainability. Recovered energy and subsidies will increase the NPV of the system and will stimulate investment in needed infrastructure. However, the setup costs of this infrastructure may be very high. Extended MRP theory can serve as a good tool for evaluating the viability of such investments. According to the interpretation provided above, individual positive generalized output energy sub-matrices can be written in general form as:

$$\tilde{\mathbf{E}}_{14}^G(\rho) = \tilde{\mathbf{\Delta}}_{14}^{pr}(\rho)\tilde{\mathbf{E}}_{14}^{G^{tr}}(\rho) = \begin{bmatrix} 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \\ \hline e^{-\rho(\Delta_{14}^{14})^{pr}} & \dots & 0 & \\ \vdots & \ddots & \vdots & \\ 0 & \dots & e^{-\rho(\Delta_m^{14})^{pr}} & \end{bmatrix} \begin{bmatrix} \hat{\epsilon}_{(2n+1)1}^{14}g_{(2n+1)1}^{14} & \hat{\epsilon}_{(2n+1)2}^{14}g_{(2n+1)2}^{14} & \hat{\epsilon}_{(2n+1)n}^{14}g_{(2n+1)n}^{14} \\ e^{-\rho(\Delta_{(2n+1)1}^{14})^{tr}} & e^{-\rho(\Delta_{(2n+1)2}^{14})^{tr}} & e^{-\rho(\Delta_{(2n+1)n}^{14})^{tr}} \\ \hat{\epsilon}_{(2n+2)1}^{14}g_{(2n+2)1}^{14} & \hat{\epsilon}_{(2n+2)2}^{14}g_{(2n+2)2}^{14} & \hat{\epsilon}_{(2n+2)n}^{14}g_{(2n+2)n}^{14} \\ e^{-\rho(\Delta_{(2n+2)1}^{14})^{tr}} & e^{-\rho(\Delta_{(2n+2)2}^{14})^{tr}} & e^{-\rho(\Delta_{(2n+2)n}^{14})^{tr}} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{\epsilon}_{m1}^{14}g_{m1}^{14}e^{-\rho(\Delta_{m1}^{14})^{tr}} & \hat{\epsilon}_{m2}^{14}g_{m2}^{14}e^{-\rho(\Delta_{m2}^{14})^{tr}} & \dots & \hat{\epsilon}_{mn}^{14}g_{mn}^{14}e^{-\rho(\Delta_{mn}^{14})^{tr}} \end{bmatrix}; \tag{14}$$

$$\tilde{\mathbf{E}}_{44}^G(\rho) = \tilde{\mathbf{\Delta}}_{44}^{pr}(\rho)\tilde{\mathbf{E}}_{44}^{G^{tr+\hat{E}}}(\rho) = \begin{bmatrix} e^{-\rho(\Delta_{14}^{44})^{pr}} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & e^{-\rho(\Delta_{m-2n}^{44})^{pr}} \end{bmatrix} \begin{bmatrix} \hat{\epsilon}_{11}^{44}g_{11}^{44} & \hat{\epsilon}_{12}^{44}g_{12}^{44} & \dots & \hat{\epsilon}_{1n}^{44}g_{1n}^{44} \\ e^{-\rho(\Delta_{11}^{44})^{tr}}e^{-\rho(\Delta_{11}^{44})^{\hat{E}}} & e^{-\rho(\Delta_{12}^{44})^{tr}}e^{-\rho(\Delta_{12}^{44})^{\hat{E}}} & \dots & e^{-\rho(\Delta_{1n}^{44})^{tr}}e^{-\rho(\Delta_{1n}^{44})^{\hat{E}}} \\ \hat{\epsilon}_{21}^{44}g_{21}^{44} & \hat{\epsilon}_{22}^{44}g_{22}^{44} & \dots & \hat{\epsilon}_{2n}^{44}g_{2n}^{44} \\ e^{-\rho(\Delta_{21}^{44})^{tr}}e^{-\rho(\Delta_{21}^{44})^{\hat{E}}} & e^{-\rho(\Delta_{22}^{44})^{tr}}e^{-\rho(\Delta_{22}^{44})^{\hat{E}}} & \dots & e^{-\rho(\Delta_{2n}^{44})^{tr}}e^{-\rho(\Delta_{2n}^{44})^{\hat{E}}} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{\epsilon}_{(m-2n)1}^{44}g_{(m-2n)1}^{44} & \hat{\epsilon}_{(m-2n)2}^{44}g_{(m-2n)2}^{44} & \dots & \hat{\epsilon}_{(m-2n)n}^{44}g_{(m-2n)n}^{44} \\ e^{-\rho(\Delta_{(m-2n)1}^{44})^{tr}}e^{-\rho(\Delta_{(m-2n)1}^{44})^{\hat{E}}} & e^{-\rho(\Delta_{(m-2n)2}^{44})^{tr}}e^{-\rho(\Delta_{(m-2n)2}^{44})^{\hat{E}}} & \dots & e^{-\rho(\Delta_{(m-2n)n}^{44})^{tr}}e^{-\rho(\Delta_{(m-2n)n}^{44})^{\hat{E}}} \end{bmatrix}. \tag{15}$$

We suppose that energy is recovered at the moment when the disassembly process of element j ends completely. Production (disassembly) lead times of energy will consequently always be the same as the lead times for recovered elements, covered in generalized output matrix $\tilde{\mathbf{G}}(\rho)$. In addition, when recovering energy from waste elements (Fig. 4), the lead times $e^{-\rho(\Delta_{ij}^{44})^{\hat{E}}}$ for decomposition of waste elements should also be considered inside sub-matrix $\tilde{\mathbf{E}}_{44}^G(\rho)$.

2. Numerical example

Simple numerical example will be used to present energy as an input in production and recycling activities. Final product A is assembled using BOM, as shown in Figure 5. During each transition from the lower to the higher activity cell, 20% of material flow goes directly to recycling. Waste elements must be replaced with new purchases on the market.

The activity vector $\hat{\mathbf{P}}$ which denotes batch sizes at each stage of the system for this numerical example is:

$$\hat{\mathbf{P}} = [1000 \ 2500 \ 12500 \ | \ 1000 \ | \ 1000 \ | \ 1000 \ 2500 \ 12500]^T. \tag{16}$$

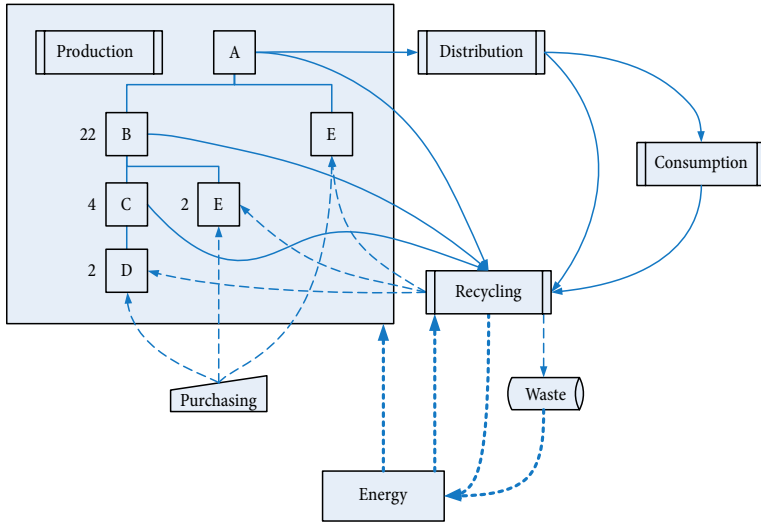


Fig. 5. Presentation of the assembly of final product A (BOM) and cyclical material flows through all subsystems

Further, if we define initiation times $\tilde{\mathbf{t}}(\rho)$:

$$\tilde{\mathbf{t}}(\rho) = \begin{bmatrix} e^{-8\rho} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & e^{-5\rho} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & e^{-3\rho} & 0 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & e^{-11\rho} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e^{-14\rho} & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 0 & e^{-17\rho} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & e^{-20\rho} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & e^{-23\rho} \end{bmatrix} \tag{17}$$

and lengths of the cycles $\tilde{\mathbf{T}}(\rho)$:

$$\tilde{\mathbf{T}}(\rho) = \begin{bmatrix} (1-e^{-4\rho})^{-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & (1-e^{-8\rho})^{-1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-e^{-16\rho})^{-1} & 0 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & (1-e^{-8\rho})^{-1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & (1-e^{-10\rho})^{-1} & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 0 & (1-e^{-4\rho})^{-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & (1-e^{-5\rho})^{-1} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & (1-e^{-16\rho})^{-1} \end{bmatrix} \tag{18}$$

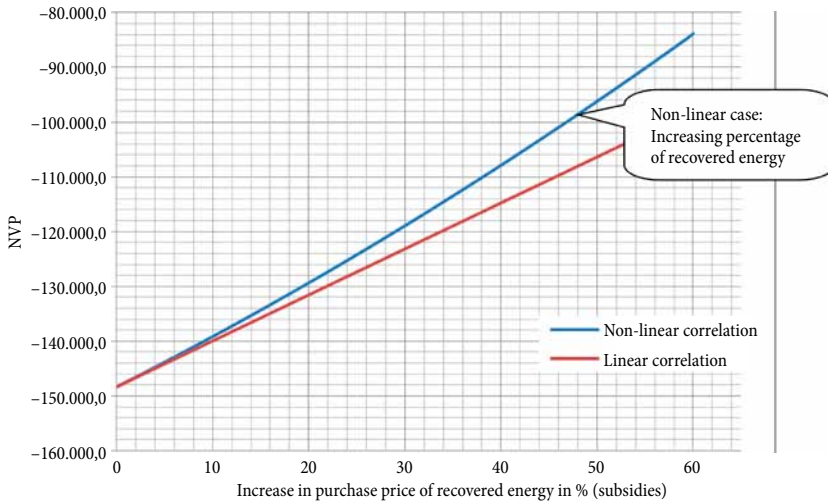


Fig. 6. The impact of energy purchase price subsidies on overall NPV of energy in the system

energy recovery facilities and technologies which will increase the quantity or quality of recovered energy. Consequently, the percentage of the recovered energy in the system will increase and the curve is not linear anymore.

Discussion and conclusions

This study proves that extended MRP theory is a useful tool for observing the wider aspects of environmental issues at the macroeconomic level and their impact on decisions made on micro level. Decision-making should not be isolated to individual activity cell alone. Global observation of the complete supply chain is crucial for understanding the impact of all externalities on the quality of living on the planet. The presented model allows for the observation of behavior for each single entity at the lowest level of the supply chain. Energy management plays an important role in determining the sustainability and reuse of available resources. This is especially important considering that sources of energy that are not renewable (*i.e.*, fuel). The introduction of generalized input and output energy matrices $\tilde{\mathbf{E}}_H(\rho)$ and $\tilde{\mathbf{E}}_G(\rho)$, as they are presented in this paper, provides the opportunity to fully observe the energy impact on the global supply chain. Calculation of the NPV for the global supply chain and its profitability is dependent on the locations of activity cells. Every location determines its own energy costs and eventual subsidy levels as well as the impact on the environment. Additionally, this environmental impact could be further analyzed from the pollution point of view. The output of the energy, which is not transformed to usable energy during assembly or the distribution process, is usually treated as pollution (*i.e.*, greenhouse gas emissions). The pollution causes environmental damage, which should be considered in the NPV of the entire system. Pollution can outweigh the positive effects of the supply chain, meaning that the system becomes uneconomical after considering the

energy emissions. In such a case, a negative NPV will show inefficiency in the supply chain and its negative influence on the quality of living in general. These negative outputs can be described in a generalized output matrix with the following structure:

$$\tilde{\mathbf{E}}_G(\rho) = \begin{bmatrix} \tilde{\mathbf{E}}_{11}^G(\rho) & 0 & 0 & \tilde{\mathbf{E}}_{14}^G(\rho) \\ 0 & \tilde{\mathbf{E}}_{22}^G(\rho) & 0 & 0 \\ 0 & 0 & \tilde{\mathbf{E}}_{33}^G(\rho) & 0 \\ 0 & 0 & 0 & \tilde{\mathbf{E}}_{44}^G(\rho) \end{bmatrix},$$

where $\tilde{\mathbf{E}}_{11}^G(\rho)$ denotes emissions from production, $\tilde{\mathbf{E}}_{22}^G(\rho)$ from distribution and $\tilde{\mathbf{E}}_{33}^G(\rho)$ from consumption sub-process.

The complexity of the presented model increases with the introduction of new parameters. Optimal energy use is determined by production functions, which influences optimal return rates from individual material flows in the system, as has been presented in some previous works. The return rate directly affects reuse of the elements and consequently the revenue part of the NPV for the system, which is also affected by taxation of the disposal of waste elements. The quantity of input and output energy is strongly connected to these factors, and it is the subject of market prices and subsidies for the energy. Observation of such a complex system becomes difficult from an analytical perspective. Approaches for better understanding of the entire system also for pedagogical purposes and study of correlations between individual parameters with some further simulations will be subject of further study as well as developments of algorithms for user friendly package.

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Danijel KOVAČIĆ received BSc Degree in Economics (2004) and PhD of Information-Management Science Degree at University of Ljubljana, Slovenia in 2013. Under supervision of Professor Marija Bogataj he wrote the thesis: *Ekonomsko-okoljsko ravnotežje v razširjeni teoriji planiranja materialnih potreb* (=Economic-Environmental Balance in the Extended MRP Theory). Since 2014 he is the member of MEDIFAS. He published three articles in Central European Journal of Operations Research. He is also author of eight papers in proceedings of international conference, one chapter of book and co-author of the book *The evaluation of virtual activities in global supply chains*.

Marija BOGATAJ received Math. BSc Degree (1974), MSc Degree (Operations Research, 1978) and Doctor of Engineering Science Degree at University of Ljubljana, Slovenia in 1983. She started as a lecturer at University of Maribor. As Professor of Operations Research and Statistics of University of Ljubljana she was also Dean of Faculty of Maritime Studies and Transportation 1993–1999. She established the research group CERRISK already at University of Ljubljana, but now she is leading this research group now at MEDIFAS. During 38 years of teaching at University she was member of many Scientific Committees in international, Slovenian, Spanish, Czech and Croatian Journals and Proceedings and member of Editorial Boards. She is the elected member of ISIR Executive Board (International Society for Inventory Research). In the last 20 years she was visiting professor at many EU Universities. She is author, co-author, or editor/co-editor, of 30 books, author or co-author of 172 articles, essays and working papers, of which 70 have been published in highly ranked scientific journals or are accepted for publication. She was supervisor of 4 completed doctoral theses, 10 master theses and many diploma works. Now she is supervisor of 4 doctoral theses at University of Ljubljana and Faculty of Organizational Studies Novo mesto. In the last 10 years she was invited to have lectures or evaluator for graduate students at: Universidad Politecnica de Cartagena, Spain, Karol Adamecki University of Economics, Katowice, Poland, Economic University of Prague, Czech republic, Linköping Institute of Technology, Sweden, Frankfurt, Viadrina University, Germany. She was/is the Invited Editor of International Journal of Production Economics 2010–2013 and 2015–2016 (special issue “Closed Loop Supply Chain” which will largely cover the latest research results in the field of economic efficiency and environmental issues of supply systems in cities and regions) and member of the editorial boards of seven other journals. She was the leading researcher or participated substantially at 49 research projects, 5 of them have been the European projects. She is founding member of MEDIFAS and Head of CERRISK department. She was visiting researcher at Mobile Assistance in St.John’s Innovation Center, Cambridge.