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ABSTRACT

Mathematical optimization can be used to increase the effectiveness of economic planning in socialist economies. Cockshott and Cottrell [*Towards a New Socialism*, Spokesman: 1993] have proposed a model of socialism in which optimal planning is made responsive to consumer demand. A point of contention has been the emphasis on labor values in their model. The use of labor values could mean that the environmental impact of production is insufficiently reflected in planning targets. This paper discusses how alternative values (opportunity cost valuations, OCs) can be calculated using linear optimization and presents a computer simulation of a socialist economy based on these values. An agent-based consumer model was developed to model the behavior of consumers. An alternative version of the simulation based on labor values is used for comparison. It is found that in specific circumstances the use of OCs does indeed result in a stronger emphasis on more environmentally friendly production than the labor value model. Relevant literature on optimal planning, distribution under socialism and valuation will be reviewed, followed by a presentation of the simulation and a discussion of some of its results for a series of small test economies.

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1. Introduction

Mathematical optimization can be used to increase the effectiveness of economic planning in socialist economies (Kantorovich 1960, 1965; P. Cockshott 2010; P. Cockshott 2019). P. Cockshott and Cottrell (1993) have proposed a model of socialism (TNS model)[1] in which optimal planning is made responsive to consumer demand. Elsewhere, I have argued that the emphasis on labor values in the TNS model means that the environmental impact of production is insufficiently reflected in planning targets and suggested using some other method of valuation (Dapprich 2018). This paper discusses how a variant of opportunity cost values (OC) can be calculated using linear optimization and presents a computer simulation of a socialist economy based on them. An agent-based consumer model was developed to model the behavior of consumers. An alternative version of the simulation based on labor values (LV) is used for comparison. It is found that the OC model does indeed put a stronger emphasis on more environmentally

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[1]TNS stands for Towards a New Socialism, the name of their book.

friendly production than the LV model in some of the scenarios investigated. Relevant literature on optimal planning, distribution under socialism and valuation will be reviewed, followed by a presentation of the simulation and a discussion of some of its results for a series of small test economies.

2. Literature Review

2.1. Optimal Planning

In recent decades, Chinese political economy has seen a shift toward the use of markets. Rather than being in conflict with socialist principles, Guoguang Liu, Enfu Cheng, and Zuyao Yu see markets as necessary for an efficient economic organization (Zhang 2020). However, this may be dismissing the possibility of production planning too quickly. While market-like mechanisms may make sense in the distribution of consumer goods (see Section 1.2), they are not necessary for production planning.

Historical Soviet-type economies used the method of material balances to derive a production plan. The main concern of planners was to ensure consistency of inputs and outputs (Montias 1959). While material balancing makes sure that the plan is feasible, it does not ensure that it is the best of all feasible plans. Soviet mathematician Leonid Kantorovich noted significant problems in the economy of the USSR that could be amended by improved planning methods:

> No less significant are the indirect losses caused by the improper utilization of resources. As they are not recorded they are less noticeable. For example intricate equipment is used for simple work, with low efficiency, while in other places, where it could be most effective, the absence of this equipment causes delays or necessitates the use of primitive methods. This is also true of materials. Particularly frequent are the losses due to the lack of flexibility in allocation, resulting in the lack of small quantities of any necessary material becoming a hindrance to raising output. (Kantorovich 1965, p. xxiii)

Kantorovich subsequently developed linear programming as a way of deriving an optimized production plan and avoiding the ineffective use of productive resources (Kantorovich 1960, 1965). The Towards a New Socialism model (TNS) by P. Cockshott and Cottrell (1993) relies on a similar method of plan optimization, developed by P. Cockshott (1990). The TNS model also provides a wider framework in which optimal planning can be applied and through which the plan target can be made responsive to consumer demands. Greenwood (2007) argued in an earlier issue of this journal that the TNS model fails to solve the calculation problem (von Mises 1920). This failure can at least in part be attributed to its reliance on labor values. The model presented here does not rely on labor values and is thus not affected by this objection.

A related concern about socialist planning is that necessary economic information might not be available to planners (Hayek 1945). While I will not go into a detailed response to the information argument here, I believe that the information input required by the presented model, such as inputs and outputs of available production techniques, can be gathered and made available to planners. Other knowledge, which may be more tacit and local in nature, is not required to run the specified planning algorithms and would thus not need to be known by a central planning agency.

The planning literature has long considered how environmental constraints can be taken into account in the planning process (Wirl, Infanger, and Unterwurzacher 1987). The basket of produced commodities may have to be reduced in response to such limitations. Wirl, Infanger, and Unterwurzacher (1987, p. 301) suggests that in socialist economies the choice over which products will be limited will be a top-down rationing decision. In Section Three, I demonstrate how my model allows for this decision to be made in response to consumer demand instead.

2.2. Distribution and Valuation Under Socialism

Socialists in the 19th century, including Marx (1999, 2007), suggested that consumer products could be distributed through vouchers which represent a certain amount of labor time:

> [The worker] receives a certificate from society that he [sic] has furnished such-and-such an amount of labor (after deducting his labor for the common funds); and with this certificate, he draws from the social stock of means of consumption as much as the same amount of labor cost. The same amount of labor which he has given to society in one form, he receives back in another. (Marx 1999, part 1)

The price of various consumption products is, according to Marx, to be determined by the amount of labor time necessary to produce them, i.e., their labor value. Demonstrating that it was indeed possible to calculate such labor values was of great concern to socialists in the early 20th century (Chaloupek 1990; Appel 1930; Leichter 1923), though this literature is for the most part unclear about how such values ought to be used in a socialist economy.

Not all goods and services need to be distributed via such labor vouchers though, and Marx vehemently insisted that part of the social product should be assigned to common funds. These common funds would be used to facilitate the social provisioning of goods. For example, healthcare and education might not require recipients to use labor vouchers and would instead be made available freely at the point of use. The social provisioning of goods is not included in the presented simulation for simplicity reasons, but should certainly play an important role in any real-world implementation of socialism.

Market socialists (Dickinson 1930, 1939; Lange 1936) proposed that market clearing prices be used instead of labor values to ensure an optimal distribution of goods. Clearing prices are to be determined by a trial and error process in which prices are successively adjusted until supply matches demand. This is influenced by Walras' tâtonnement process (Walras 2014). The TNS model (P. Cockshott and Cottrell 1993) combines these two approaches by accepting the use of market clearing prices for consumer products only. Clearing prices are then compared to labor values in order to determine how the planning target ought to be adjusted for future planning periods. Should prices exceed values, the demand for this product justifies expanding its production and the target for the product is increased. Should the opposite be the case, the target for the product has to be reduced. This process makes the planning target responsive to consumer demand.

I have previously argued that the use of labor values in the TNS model does not sufficiently consider the environmental impact of production and proposed using some alternative system of valuation instead (Dapprich 2018). One potential candidate for this is objectively determined valuation (ODVs), which Kantorovich derived from his method of linear programming (Kantorovich 1960, 1965; P. Cockshott 2010). Later linear programming literature (Pack 1979) considers cost as opportunity cost and uses linear optimization to derive shadow prices. This usually assumes that the product is sold for profit, which is incompatible with a planned socialist economy. I have developed a variant of shadow pricing based on the notion of opportunity cost for the use in socialist economies that will be discussed in Section 2.1.3.

2.3. Ownership, Coordination and Participation

Somewhat more recent socialist literature has given significant attention to the ownership status of enterprises, coordination between enterprises and democratic participation in socialist economies (Devine 1992; Albert 2004; Miller 1989; Nove 1983; Roemer 1994; Horvat 1982). While it is beyond the scope of this paper to provide an extensive critical discussion of the various contributions to this debate, it is nonetheless worthwhile to position the presented model within this literature.

One key question has been whether workers or other individuals should have distinctive ownership rights to enterprises in a socialist society. While eastern socialism was mostly focused on state-ownership, Horvat (1982) proposed that enterprises should be owned by their workers. Some market socialists have also proposed some form of (limited) stock ownership of enterprises by private citizens (Roemer 1994). Both of these approaches represent significant compromises on the socialist demand for collective ownership of the means of production. In contrast, the model presented here assumes that all enterprises and means of production are owned by the public in general. Instead of each enterprise being owned by its workers or each citizen owning some share of some enterprise, all enterprises are owned by all workers and non-working citizens alike and are administered collectively or through planning institutions accountable to the general public.

Market socialists (Lange 1936; Nove 1983; Miller 1989; Roemer 1994) have emphasized the independence of individual enterprises and use of market mechanisms, though some of these proposals combined this with some form of central planning. The contradiction between independence on the one hand and central planning on the other has been highlighted by Blackburn (1991) and is also noted by Devine (1992). My model does not have the same problem. While the model adopts the idea of market clearing prices from market socialism (Dickinson 1930, 1939), I do not give the same importance to the independence of enterprises. The model should instead be seen as a method for determining a production plan for the entire economy that enterprises are obliged to adhere to. Individual enterprises contribute to the planning process mostly through the provision of information about available resources and productive capacities. They do not compete on a market. While there is something akin to a market in consumer goods that distributes the items to individual consumers, there is no market in productive resources. The allocation of productive resources is instead determined through optimal planning.

The participatory planning approaches of Albert (2004) and Devine (1992) have emphasized the participation of citizens in planning decisions that affect them.

Devine (1992) suggests that individual decisions would involve some kind of negotiation between stakeholders. My model does not involve such negotiation and instead uses algorithmic optimization under given constraints to determine a production plan. This ensures that the resulting plan is optimal. This means that it produces as much as is possible without violating given constraints. Negotiation does not guarantee such an optimal outcome. However, the use of an algorithmic method does not mean that citizens cannot influence the planning process at all.

There are two main ways that citizens could influence production plans. As consumers, their consumption behavior contributes to the demand for certain consumer goods, which affects whether production targets for these goods are increased or decreased. This attributes a significant degree of individual freedom to citizens. Not only are they allowed to choose freely which consumer products to purchase with their tokens, but their choices will also be reflected in production targets. The second way that citizens can influence planning is as democratic constituents. Planners should be democratically accountable and must abide by a democratic decisions. A democratic decision may for example limit the permissible emission of greenhouse gases. Such decisions are reflected in the planning process as constraints which any production plan must not violate.

I expect that an objection to my model will be that room for democratic participation is insufficient. It is in principle possible to view the result of the algorithmic optimizations used in my model as merely advisory. This means the democratic constituents can choose to abide by the optimized production plan or not, which I believe addresses this objection in a sufficient manner. I am, however, not aware of any good reason that citizens would ever have to do this.

Hahnel and Kerkhoff (2020) discussed how participatory planning can be used for investment planning, so that plans for longer time periods can be drawn up. A limitation of my model is that it does not make such a consideration. Instead, capital stock is seen as constant. However, P. Cockshott (2019) discusses how optimal planning techniques can in principle be used to draw up multi-year plans. An integrated model that combines optimal multi-year planning with consumer feedback is still missing from the literature and may well be the subject of future research.

3. The Simulation

The simulation considers several successive plan periods for a model economy. Simple reproduction is assumed, meaning there is no economic growth or expansion of the means of production. Production possibilities are specified by tables resembling Leontief-style Input-Output matrices (Leontief 1986). Each column represents a possible method of production. In the first table (see Table 1) the rows represent an item that might be used as a production input. The table thus specifies how much of each item is needed to perform the production method at an intensity of one. Using the farming method at an intensity of one requires 2 units of corn, 1.05 units of coal, 1.09 units of iron and 2 units of direct labor. Table 2 specifies in an analogous fashion how much of each item is produced with the various methods when they are used at an intensity of one. The farming method produces 11 units of corn. This is an example for an economy with only four different products and production methods, but the simulation

Table 1. Input table based on a similar example used by P. Cockshott (2019).

	Methods			
Inputs	Farming	Coal mining	Iron mining	Baking
Corn	2	0	0	5
Coal	1.05	1.1	3	1
Iron	1.09	2	1.2	0
Bread	0	0	0	0
Labor	2	3	1.3	2.1

Table 2. Output table corresponding to Table 1.

	Methods			
Outputs	Farming	Coal mining	Iron mining	Baking
Corn	11	0	0	0
Coal	0	13	0	0
Iron	0	0	17	0
Bread	0	0	0	23

is written in a way that it can in principle be applied to economies with any number of production techniques or products.

It is assumed that most productive resources are produced at the same time as they are being used in production. Other input requirements, like land, labor or capital stock, which cannot simply be produced within the same planning period, must be included at the bottom of the input table, but are not included in the output table. Table 1 only includes labor in Line 6. Non-produced inputs can also include deliberate environmental constraints such as a cap on greenhouse gas emissions. Emission rights are simply assumed to be a further input requirement. Section 3 compares results for test economies that do and do not include such an emission constraint.

It is also possible that some outputs can be produced using different methods, which require different inputs.[2] For example, one method for producing corn might use more energy, while another method is more reliant on direct labor. The results for one such example are discussed in Section 3.[3]

A plan target vector (see Table 3) specifies at which proportions products are to be produced for consumers. This does not consider the part of the product that gets used up in production, but only the share of the product that is actually intended for consumers. Thus the target value for iron in Table 3 is 0, as iron is only used in manufacturing. For every 6 units of corn, 7 units of coal and 10 units of bread are to be made available to consumers. For the simulation an initial plan target needs to be specified, which will then be adapted depending on consumer choices (see Section 2.2.3). There is no strict rule mandating what initial target must be chosen, however planners may choose proportions that seem sensible for the expected consumption needs of the population. For this they may also draw on available information about past consumption.

[2]The model does not currently allow for economies of scale, but since multiple methods are allowed, different scales of production could be modeled through distinct production methods. The reason that the current model is nonetheless inadequate for representing economies of scale is that there is nothing that would prevent a large scale production method from being used at a very low intensity. Preventing this would require some additional constraint that is not currently included in the model or shifting to a model where the intensities at which production methods are used are discrete.

[3]It is also in principle possible for one method to produce several different outputs, as is the case in industries that have some by-product, though this has not been studied for the present paper.

Table 3. Example target vector corresponding to Tables 1 and 2.

	Corn	Coal	Iron	Bread
Target	6	7	0	10

Further variables that must be specified are a resource vector, which states the amount of non-produced resources like labor or emission rights that are available for a production plan,[4] an initial price vector, and product weights, which are used in the consumer model (see Section 2.2). The overall structure of the model can be seen in Figure 1. For each plan period an optimal plan must be calculated based on the current plan target (see Section 2.1). A plan is a specification of the intensities at which various production method are to be used. Next, values of consumer items are calculated and these are then marketed to consumers using the clearing prices from the previous plan period (see Section 2.2.1). In the first period the initial target and initial prices are used. Ideally initial prices will already be close to market clearing prices, however since market clearing prices may not be known a best guess can be used instead. The prices are then successively adjusted in order to approximate market clearing prices (see Section 2.2.2). Finally, clearing prices are compared to values and the target is adjusted for the next plan period based on this comparison (see Section 2.2.3).

3.1. Linear Optimization and Valuation

In order to calculate an optimal plan, the lp_solve package for python is used. lp_solve is an open source linear programming solver which uses the simplex method, the western variant of linear programming developed by Dantzig (1954). The objective is to maximize production of consumer products at the proportions specified by the plan target. We can do this by using lp_solve to maximize production of any one consumer product (the Objective Product) while ensuring proportionality through constraints.

Environmental concerns are also taken into account through constraints, rather than being built into the objection function. One reason for this is that it is not obvious how environmental concerns should be weighted in the objective function compared to the production of consumer products. The other reason is that this allows for more deliberate control of the environmental impact of production. Environmental constraints can, for example, be chosen to correspond to physical planetary limits or politically agreed goals, such as the 1.5°C goal of the Paris Climate Agreement (UNFCCC 2015).

The simulation always uses the product represented in the first row of the input and output tables (product 1) as the Objective Product. This must thus be a consumer product (which has positive target values) and not a product that is exclusively used in production (which has target values of 0). Precise mathematical formulations of the objective function and constraints of the optimization problem are given in Sections 2.1.1 and 2.1.2 respectively.

Section 2.1.3 then explains how lp_solve is also used to calculate opportunity cost valuations. These values are not needed for deriving an optimized production plan, but will instead be used to adjust the plan target for future planning periods in response to consumer feedback. The process for this will be explained in Section 2.2.

[4] This can be seen as a flow of resources for the time period covered by the plan.

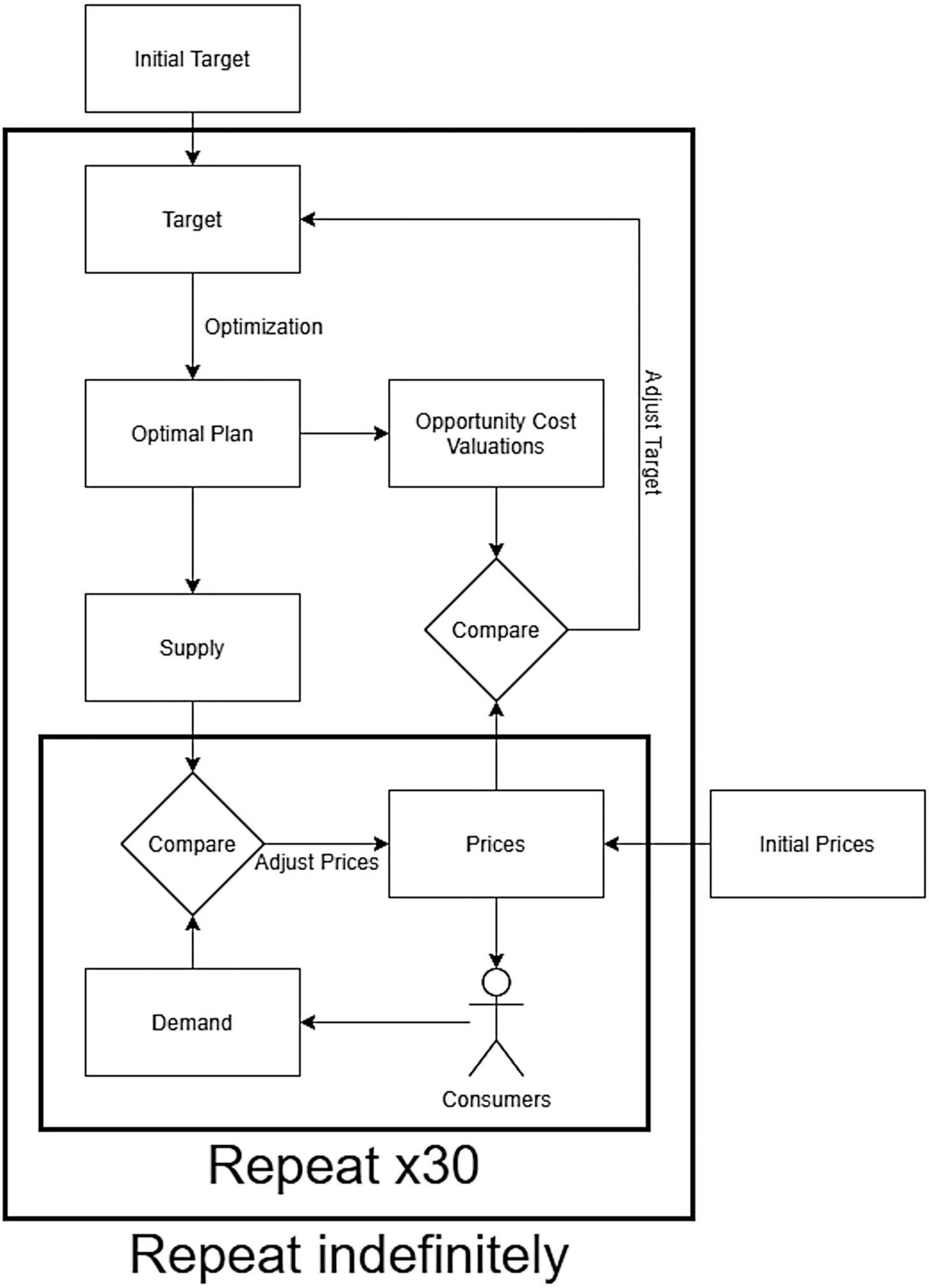

Figure 1. Overview diagram of the model.

3.1.1. Objective Function

The objective function in an optimization problem is the mathematical function that is to be maximized. In linear programming this function must be linear. Since we want to maximize the production output of an arbitrary consumer product (the Objective Product), the linear objective function consists of n variables, each representing the intensity at which one of the n production methods is used. The coefficients corresponding to each variable are given by the amount of the Objective Product produced by the corresponding production method, minus the amount used by that method. The objective function f is thus given by

$$f(M) = \sum_{i=1}^{n} (O_{i,1} - I_{i,1})M_i, \tag{1}$$

where n is the number of production methods, $O_{i,j}$ is the output of the j_{th} product of the i_{th} production method, $I_{i,j}$ is the input of the j_{th} product of the i_{th} production method and M_i is the intensity at which the i_{th} production method is used. What is considered as contributing to plan fulfillment is thus only the surplus product that is available for consumers, not the part of the overall product that is used as a production input.[5]

For the economy displayed in Tables 1 and 2, corn would be the Objective Product and the value of the objective function is given by the amount of corn that is produced in surplus of the corn that is simultaneously used in production. The objective function in this example is thus given by

$$f(M) = (11 - 2)M_1 + (0 - 0)M_2 + (0 - 0)M_3 + (0 - 5)M_4 = 9M_1 - 5M_4, \tag{2}$$

where M_1, M_2, M_3 and M_4 are the intensities at which the production methods *Farming*, *Coal mining*, *Iron mining* and *Baking* are used respectively. The parameters follow from the outputs and inputs of corn for the corresponding production method.

3.1.2. Constraints

The optimization task for lp_solve is to find the values of the variables which maximize the value of this objective function. This must, however, be done without violating any of the following constraints. There is one constraint for every type of item in the economy, except for the Objective Product. These can be divided into three distinct categories:

(a) a target constraint for every consumer product, except the Objective Product
(b) a production constraint for every product that is only used in production
(c) a resource constraint for every non-produced input requirement

Target constraints ensure that consumer products are produced in the proportions specified in the plan target by relating the amounts of the Objective Product produced to those of the other consumer products. The target constraint for the j_{th} product with target value t_j can be represented by the linear equality

$$\sum_{i=1}^{n} \left[\frac{1}{t_1}(O_{i,1} - I_{i,1}) - \frac{1}{t_j}(O_{i,j} - I_{i,j}) \right] M_i = 0. \tag{3}$$

The input requirements of each production method are subtracted from the output so that only the portion of products intended for final consumption is considered. This is

[5]The unit of the objective function, just as the unit of opportunity cost in Section 2.1.3, is simply the unit in which the Objective Product is measured, i.e., pieces, tons, kilogram, liters,…. Changing from tons to kg would increase the value of the objective function by a factor of 1000. This is not a problem, but shows that one has to be consistent in the use of units.

because the plan target only specifies how much of various products is supposed to be made available to consumers and does not constraint the use of goods as productive resources.

For the economy in Tables 1 and 2, there will be one target constraint for coal and one target constraint for bread. These will respectively be given by

$$\frac{33}{20}M_1 - \frac{17}{10}M_2 + \frac{3}{7}M_3 - \frac{29}{42}M_4 = 0, \tag{4}$$

and

$$9M_1 - 29M_4 = 0. \tag{5}$$

Production constraints ensure that no more of a product is needed as input than is produced. There is no need to add production constraints for products that are used in both production and final consumption, as this condition is already satisfied due to the corresponding target constraint as long as the objective function is positive. For all other products, the production constraint can be expressed as the inequality

$$\sum_{i=1}^{n}(O_{i,j} - I_{i,j})M_i \geq 0, \tag{6}$$

where j is the number of the product to which the constraint corresponds.[6]

For our illustrative economy, only iron has a corresponding production constraint, as it is the only product not used by consumers. The constraint is given by

$$-1.09M_1 - 2M_2 + 15.8M_3 \geq 0. \tag{7}$$

The resource constraints limit how much of any non-produced input, or inputs that are produced independently of the plan, can be used for a production plan. Depending on the concrete example studied, this could include labor, land, limited machinery or resources and even emission rights, which can be treated as input requirements for the purpose of the simulation. The resource constraint for the item in the j_{th} row of the input table takes the form of the inequality

$$\sum_{i=1}^{n} I_{i,j}M_i \leq R_j, \tag{8}$$

where R_j is the entry in the resource vector corresponding to the j_{th} item. R_j thus represents the limit to how much of the item can be used in the time period covered by a production plan. In our illustrative economy, labor is the only non-produced input. The corresponding resource constraint is given by

$$2M_1 + 3M_2 + 1.3M_3 + 2.1M_4 \leq R_1, \tag{9}$$

where R_1 is the amount of labor available for the time period covered by the plan.

An optimized production plan is given by the intensities M_i at which various production methods are to be used such that the objective function $f(M)$ is maximized without

[6]The simulation always uses the strict inequality operator instead due to a limitation in one of the computer scripts used. This makes little difference.

the intensities violating any of the constraints. This optimized plan, as well as the value of the maximized objective function, are calculated using lp_solve.

3.1.3. Valuation

The simulation uses a novel system of valuations (OC), based on opportunity cost, which are also calculated using lp_solve. A comparison of prices and opportunity costs determines how the plan target will be changed (see Section 2.2.3). The underlying idea of these valuations is to consider the opportunity cost in terms of plan fulfillment (how much is produced at the proportions specified by the plan target) of a single unit of a product. The OC of an item is the answer to the question 'How many more consumer products (at the proportions specified in the plan target) could be produced if we did not have to expend the resources for one unit of the item?'. It is measured as an increase in the optimized objective function, as defined in Section 2.1.1.

To calculate the OC of a product the optimization discussed in the previous subsections is repeated, only this time an additional production method with one unit of the item as output is considered. The method does not require any inputs, allowing the product to be produced freely. But since only one unit of the product should be produced freely, the intensity of that method is limited to one using an additional constraint. Because one unit can be produced freely, slightly more can be produced overall. This additional output can be measured as an increase in the value of the optimized objective function. This increase is recorded as the OC value for that product. The OC value v_i for one unit of product i is thus given by:

$$v_i = y_{\max,i} - y_{\max}, \tag{10}$$

where $y_{\max}$ is the optimized value of the objective function $f(M)$, with M subject to normal constraints, while $y_{\max,i}$ is the optimized value of the objective function $f(M)$, with M subject to modified constraints which allow for the free production of one unit of the ith product.[7]

We can illustrate how the valuation process works using the example given in Tables 1 and 2. Under a given plan target and resource constraint, lp_solve determines that the economy is able to produce 1161.26 units of corn, which is used as the Objective Product (see Sections 2.1.1 and 2.2.2 for a precise mathematical formulation of the objective function and constraints). We then run lp_solve again, but this time we include the fictitious *free corn* method and adjust the objective function and constraints according to the general formulations in Sections 2.1.1 and 2.2.2. The *free corn* method M_5 is able to produce one unit of corn without any production inputs. An additional constraint ensures that only one unit of corn can be produced in this way, by limiting the intensity of the method M_5 to a maximum of one:

$$M_5 \leq 1. \tag{11}$$

When including the *free corn* method the value of the optimized objective function, as determined by lp_solve, increases from 1161.26 to 1161.57. This increase of 0.31 is thus recorded as the OC of one unit of corn.

[7]The unit of all OC values is given by the unit of the objective product, e.g., tons of corn. However, the unit we might ascribe to the values has no impact on how the algorithm operates and can thus be safely ignored.

The process has to be repeated for every consumer product. In this illustrative example, the value of the optimized objective function increased by 0.19 with one free unit of bread and by 0.31 with one free unit of coal. Therefore, these are recorded as the values of bread and coal respectively. It is not necessary to calculate the OCs for non-consumer products as they will not be needed in plan target adjustment, but this could in principle be done using the same method. However, a major drawback of this method of valuation remains that it requires a number of optimizations equal to the number of consumer products in the economy. This increases computational complexity by a factor of m, where m is the number of consumer products.

For comparison purposes an alternative version of the simulation that uses labor values instead of OCs was also created. This corresponds to the original TNS model (P. Cockshott and Cottrell 1993). Each production step retains the value of inputs and adds value equal to the labor time used. When each product can only be produced by one production method, the labor values are fully determined by the input and output tables. In the hypothetical economy described in Tables 1 and 2, the value of 23 units of bread is given by the added value of 5 units of corn and 1 unit of coal, plus 2.1 for the direct labor input. Equations for the values of all products are given in the same way, which yields a set of linear equations:

$$\begin{aligned} 11v_1 &= 2v_1 + 1.05v_2 + 1.09v_3 + 2 \\ 13v_2 &= 1.1v_2 + 2v_3 + 3 \\ 17v_3 &= 3v_2 + 1.2v_3 + 1.3 \\ 23v_4 &= 5v_1 + 1v_2 + 2.1. \end{aligned} \tag{12}$$

v_1, v_2, v_3 and v_4 are the labor values of corn, coal, iron and bread respectively.

Should more than one production method be used for the same product, the labor values also depend on the intensities at which various production methods are used. In that case the left side of the linear equation for an item will show the labor value of the total product and the right side the sum of the labor values of the total inputs used in the economy to produce this product. This still yields a set of linear equations with one equation for every product type. Linear dependencies can only occur if a production method has more than one product. As long as such cases are not considered, the linear equations can thus be solved to determine labor values for all products. When a product can be produced by more than one method, labor values may change depending on which production methods are used since this may affect average labor usage. In our example this is not the case and the set of linear equations (11) is solved by $v_1 \approx 0.27$, $v_2 \approx 0.27$, $v_3 \approx 0.13$ and $v_4 \approx 0.16$.

3.2. Consumer Model and Target Adjustment

Once the optimal plan and OCs are calculated, consumer products are marketed to consumers at initial prices. This is repeated several times with prices each time being adjusted based on a comparison of supply and demand to approximate the market clearing prices at which demand and supply match. In a real economy the demand would be known from the observed purchasing behavior of consumers. For the purpose of the simulation an agent-based consumer model was developed which yields demand that is responsive to prices. Once market clearing prices have been approximated the plan target is adjusted for the next plan period, based on a comparison of prices and OCs. A new optimized production plan is then calculated for this new plan target and the whole process is repeated. In the following, I will explain how the consumer model works and how prices and the plan target are adjusted.

3.2.1. Consumer Model

The consumer model determines demand based on prices and weights assigned to each consumer product. Weights must be specified for each consumer good before the simulation is run and do not change in the course of the simulation. They are the same for all consumers. This does not imply that all consumers have the same preferences and make the same choices, as individual choices are determined by chance. Weights simply determine how likely it is for a random consumer to choose a product.

There are 1000 consumers in total and they each have 100 credits to spend. Demand is calculated for each consumer individually and then added up. Both weights and prices influence how likely an individual consumer is to buy a product. At the same price a product with a higher weight will be bought more often. With the same weights, a product with a lower price will be bought more often. This is achieved by a two step process (see Algorithm 1). First, a product is chosen with a probability proportionate to its weight. A product with weight 2 is twice as likely to be chosen as a product with weight 1 and so on. The weights must be specified before the simulation commences, depending on what one wants to test for. For the tests presented in Section Three I have assigned both consumer items an equal weight of 1, so that any difference that is observed cannot be due to a difference in weights.

Next, it is checked whether the consumer has enough credit left to buy the product. If she does, the demand for that product is increased by one and the price subtracted from the consumer's budget. This process is repeated until the consumer cannot afford the selected item 5 times in a row. We can interpret the process with the help of a shopping list. Each shopper has an individual, ordered and infinite shopping list. Items can appear several times in the shopping list. For example, the item on the top of the shopping list might appear again further below. Items with a higher weight appear more often on the list. The ordering of the list represents how important the item is to the shopper. She will first attempt to buy the first item on the list, then the second and so on. Only when she cannot afford an item does she skip it. She will stop shopping only when she can't afford five items in a row, because at this point she concludes that she cannot afford anything else. She never reaches the end of the shopping list, as it is infinite. Only running out of credit will cause her to stop shopping.

There are several unrealistic assumptions in this model. In reality it might happen that a product is not bought because it is deemed too expensive, even though it could technically be afforded. But we must keep in mind that the simulated consumers would not be part of any attempt to implement this model of socialism in the real world. In the real world, the consumers are actual people. The consumer model is only needed for testing how the model of socialism responds to consumer demand. For this it is primarily important that demand is responsive to prices. Without price responsive demand, there can be no market clearing prices and the model would not make sense. So we mostly need our simulated consumers to be responsive to prices, which they are.

Price-responsiveness is significant as long as consumers can only afford a small number of products.[8]

Algorithm 1 Consumer Model

```
demand[i] ← 0 for all products i
for 1000 do
  budget ← 100
  j ← 0
  while j < 5 do
    product ← random product(weights)
    if price[product] ≤ budget then
      demand[product] ← demand[product] + 1
      budget ← budget - price[product]
      j ← 0
    else
      j ← j + 1
```

3.2.2. Clearing Prices

In order to approximate clearing prices at which supply and demand match, the price for each consumption good is adjusted in proportion to the difference between the supply of that product, as determined by the optimized production plan, and demand for it, as determined by the consumer model (see Algorithm 2). The supply of an item is the amount of that item that is produced in excess of what is used in production.

The examples discussed in this paper used a proportionality factor of 0.3. So a 10% difference between supply and demand would lead to a 3% adjustment of prices. The consumer model is then run again with the new prices and the process is repeated a total of 30 times, after which there appears to be no further convergence of supply and demand. This process is modeled on a simple proportional controller.[9] It is possible that with a more complex controller or machine learning better convergence could be achieved.

Algorithm 2 Price Adjustment

for each consumer product i **do**

$$price[i] \leftarrow price[i]\left(1 - 0.3\,\frac{supply[i] - demand[i]}{supply[i]}\right)$$

We can interpret the process by imagining that each run of the consumer model represents one day. The production plan determines the supply of consumer items for that day, while the consumer model determines the demand for those items. This is repeated for a total of 30 days using the same production plan, but with successively adjusted prices for the consumer model. After the 30 day period a new production plan, using a new planning target is calculated. A problem with this interpretation is that every day demand may not be backed by supply or items might be left over for the next day, which is not currently taken into account. This is unrealistic, but makes it easier to approximate clearing prices.

[8] It would also be possible to use a mathematical model based on price-dependent demand functions. However, demand for a product should be responsive not just to the price of that particular product, but to that of competing products as well. This would require multi-variate demand functions. It would also have to be made sure that overall spending does not exceed the combined budget of consumers. Both of these are achieved in the agent-based model but may prove more difficult in a model based on demand functions.

[9] A proportional controller is any feedback control system in which a controlled variable is adjusted in proportion to the difference between the observed and desired state of a system.

3.2.3. Target Adjustment

After prices have been adapted 30 times, the simulation moves on to the next planning period. For each subsequent planning period, the previous target is adjusted based on a comparison of the opportunity cost valuations and the approximated clearing prices. The OCs are scaled, such that the OCs of the entire product are equal to its total price. Should the adjusted OC for a product be above its price, the entry in the target vector for the item is decreased. Should the OC be less than the price, the target entry is increased. Once this has been done with every consumer product the new plan target has been found and the optimal plan and OCs for the next plan period can be calculated.

Unlike in the proportional controller used for approximating clearing prices, the amount by which target entries are adjusted is independent of the difference between OCs and prices. Instead they are changed by a fixed one percent of the current target (see Algorithm 3). For the labor value variant of the simulation, which is used for comparison, labor values are used instead of OC. These must be scaled in the same way before being comparable to prices.

Algorithm 3 Target Adjustment

```
for each consumer product i do
  if price[i]>value[i] then
    target[i] ← 1.01 * target[i]
  else
    if value[i] < price[i] then
      target[i] ← 0.99 * target[i]
```

4. Results and Discussion

Though the simulation can handle much more diverse economies, it is easier to depict and understand results for a test economy that only contains two consumer products A and B. To study the effect of emission constraints we will assume that product A requires more energy to produce than B. Energy production in turn uses up emission rights. The overall labor value of A and B is nonetheless the same since B requires more direct labor (see Table 4). To make comparison as easy as possible, we will assume that the initial target, initial prices and weights for products A and B are the same (see Table 5).

Each plan period an optimal plan is calculated and the plan target for the next period adjusted. We can depict the output of consumer products corresponding to any plan as a vector/arrow in two dimensional space. The X-axis depicts the amount of product A and the Y-axis the amount of product B produced. The direction of the vector corresponds to that of the plan target.

Table 4. Input table for first test economy.

	Methods		
Inputs	Method A1	Method B1	Coal Power
A	0	0	0
B	0	0	0
Energy	2	1	0
Emission	0	0	1
Labor	1	2	1

Note: Outputs for each method are assumed to be one unit of A, B and energy respectively.

Table 5. Initial target, initial prices and weights for all test economies.

	A	B	Energy
Initial Target	10	10	0
Initial Prices	20	20	N/A
Weights	1	1	N/A

Figure 2 shows how production of consumer goods is adjusted in the labor value- and OC models when an emission constraint is introduced. The black arrow represents the product when the only resource constraint is labor, which is limited to 15,000 units. When an emission constraint of 6000 is introduced in the labor value model the product is reduced, but the proportions are not changed. This is because the labor value of both products remain the same and the target is thus not changed. Adjusted labor values are slightly increased with the emission constraint, but relative to each other they are unaltered (see Table 6, first test economy). In the OC model the value of product A is increased relative to B due to the higher emissions (see Table 6). This leads to the plan target gradually being adjusted and the proportions at which A and B are produced are thus changed significantly in later plan periods. Instead of simply producing less of both products, the economy is adapted to produce more (in relative terms) of the more environmentally friendly product B, which is considered to have a lower cost in terms of OCs. This is line with the hypothesis that the OC model gives stronger consideration to emissions in the choice of the plan target. While the planning algorithm is deterministic, the exact results can vary slightly due to the probabilistic nature of the

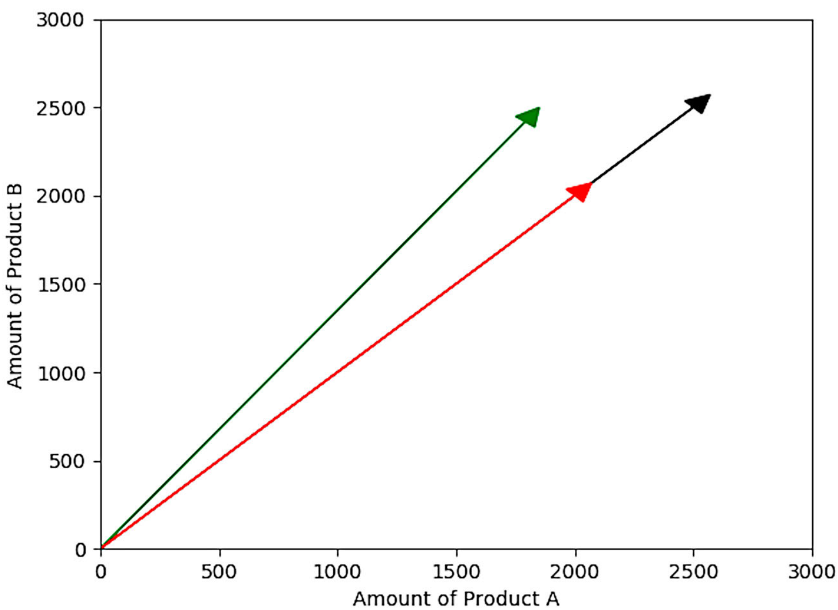

Figure 2. Amount of products A and B produced in the 20th plan period of the first test economy. Black represents the product without an emission constraint. It is the same for the OC and labor value models. With emission constraint the products are represented by red (labor value model) and green (OC model).

Table 6. Adjusted labor values and adjusted OCs of A and B for the three test economies in the 20th plan period in a typical test run using the LV and OC models respectively.

	Value(A)	Value(B)	Value(A)/Value(B)
			First test economy
No emission constraint (LV)	19.1	19.1	1.00
No emission constraint (OC)	19.2	19.2	1.00
With emission constraint (LV)	21.5	21.5	1.00
With emission constraint (OC)	29.8	14.9	2.00
			Second test economy
With emission constraint (LV)	21.3	18.8	1.14
With emission constraint (OC)	22.0	17.6	1.25
			Third test economy
With emission constraint (LV)	18.2	21.4	0.85
With emission constraint (OC)	21.8	17.4	1.25

Note: Since adjusted values are scaled to prices, the unit is one unit of consumer credit. Values in the test economies change very little over time so that the values in earlier plan periods are close to the values in the 20th plan period depicted here.

consumer model (see Section 2.2.1). However, in all five test runs of the OC model with an emission constraint, a substantial shift of the arrow in the same direction was observed every time. In contrast, none of the equivalent number of test runs without an emission constraint or with the LV model showed any substantial change of the plan target.[10]

It can be observed that in this simple economy, the OCs depend entirely on whether labor or emission constraints are the limiting factor for production (see Table 6). Without the emission constraint labor is the only limited resource hindering a further expansion of production. The OCs of products A and B are thus proportional to their labor values. With the emission constraint, labor becomes irrelevant as it is no longer the limiting factor. OCs are now proportional to energy content. This begs the question why one should calculate OCs at all and not simply use labor valuation or valuation in terms of energy, depending on what the limiting factor is. However, as we shall see in the next examples, OCs are not always identical to either labor values or energy values.

A separate consideration is that there may be more than one way to produce an item. Labor values can take land into account by virtue of the increasing amount of labor per product needed when less fertile land has to be cultivated. Perhaps a similar argument can be made in relation to emission constraints. When all emission rights are used up, labor has to be substituted for energy by using more labor intensive production methods. Table 7 considers a second test economy in which there are alternative ways of producing both A and B. While the alternative production methods are much more labor intensive, they require less energy and can thus be used when emissions are a consideration.

Figure 3 shows how production is adapted in the second test economy. All variants were again repeated 5 times, and showed similar results every time. Without an emission constraint, the optimal plan is identical to that for the first test economy, as the more labor intensive production methods are not used. With an emission constraint,

[10]The chance of the shift being in the same direction every time by chance alone is $0.5^5 \approx 3.1\%$. Since this is less than 5% the results are statistically significant. No further formal statistical analysis of any of the results was deemed necessary, as results were very consistent and any randomness in outcomes must be purely attributed to the consumer model and not the deterministic planning algorithm. It is the latter, however, that is of primary interest and the consumer model is merely used as a replacement for real consumers.

Table 7. Input table for second test economy.

	Methods				
Inputs	Method A1	Method A2	Method B1	Method B2	Coal Power
A	0	0	0	0	0
B	0	0	0	0	0
Energy	2	1	1	0	0
Emission	0	0	0	0	1
Labor	1	3	2	4	1

Note: Outputs for each method are assumed to be one unit of A for methods A1 and A2, one unit of B for methods B1 and B2 and one unit of energy for Coal Power. The third test economy is identical, except that method A2 is left out.

Method A2 sees considerable use in both the labor value- and OC models. In the labor value model, the use of A2 leads to an increase in the average labor content of product A and thus in its value (see Table 6). The resulting shift in the plan target is in this case similar to the shift observed in the OC model (see Figure 3). This demonstrates that under certain circumstances, an emission constraint can have a considerable effect on labor values and thus the plan target in the labor value model. However, as the next example shows, the result can differ significantly from the OC model.

In the third test economy it is assumed that only for the production of B there is an alternative, more labor intensive method B2. Method A2 is thus not considered and A has to be produced through the more energy intensive method A1 (as in Table 7, just without Method A2). This leads to significant use of method B2 to save energy in both models. In the labor value model this actually results in an increase in the value of B, since the average labor time used to produce B is now higher (see Table 6). We thus observe a

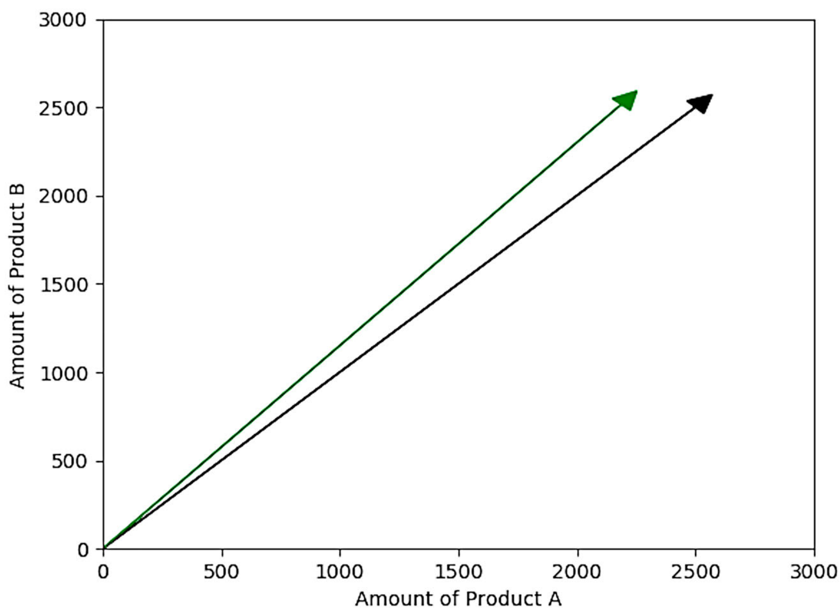

Figure 3. Amount of products A and B produced in the 20th plan period of the second test economy. As before, black represents the product without an emission constraint. With emission constraint the products are represented by green (OC model). The results of the LV model correspond almost exactly to those of the OC model and are thus not shown separately.

shift in the plan target in the opposite direction, while in the OC model we still see a shift in favor of B (see Figure 4). Again, all variants were repeated 5 times and showed similar results every time.

The availability of an alternative method B2 does not increase the opportunity cost for product B, though it does increase the labor value. This has the effect that in the labor value model the plan target is shifted in favor of A, which is the more environmentally destructive product. The OC model instead puts a stronger emphasis on the production of the eco-friendly product B. In both models the overall emissions are constrained by the same limit. So it is not the case that one model leads to higher overall emissions than the other. But they use a different measure of cost to determine what consumer products ought to be produced. In confirmation of the intuition expressed by Dapprich (2018), the labor value model does not necessarily lead to a shift of the plan target towards more environmentally friendly products. Whether the outcome of the labor value model or the OC model is deemed more appropriate depends on what one considers to be an adequate measure of cost: labor value or opportunity cost. The simulation demonstrates that these two measures of cost can differ significantly and labor value can thus not be used as a proxy for opportunity cost as measured by OCs.

Furthermore, the simulation demonstrates a sensible model for a socialist economy that uses optimal planning and consumer feedback. OCs constitute a possible measure of cost valuation that can be compared to clearing prices to decide how a target has to be adapted. Both the opportunity cost and labor value model allow to combine optimal planning with consumer feedback. Furthermore, they allow to constrain production in the face of environmental concerns. This allows to combine a direct limitation of environmental degradation with the efficiency advantages of optimal planning.

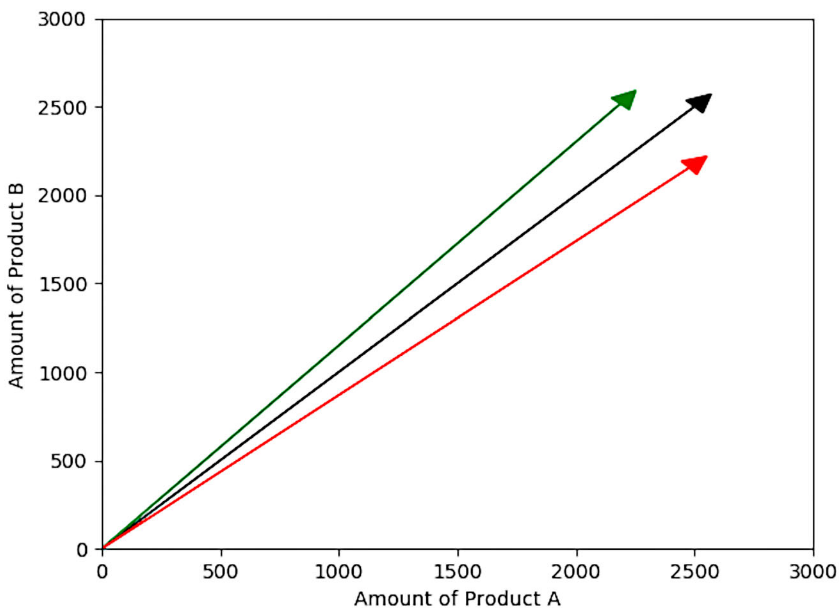

Figure 4. Amount of products A and B produced in the 20th plan period of the third test economy. As before, black represents the product without an emission constraint. With emission constraint the products are represented by red (labor value model) and green (OC model).

The main issue for application in real economies is the number and complexity of linear optimizations that has to be done to calculate opportunity cost values using the presented method.[11] However, it may well be possible that there is an easier way to calculate adequate cost valuations. The model could also be improved by using enhanced controllers for the adjustment of prices and targets.

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[11] W. P. Cockshott and Cottrell (1993) have found that plan optimizations with lp_solve are of order n^3, but also proposes a more efficient algorithm with which an optimal production plan for an economy with 200 million products can be calculated in 22 min. However, if one optimization has to be carried out to value each product, this will still take much too long.

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