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Supply chain network design and operation: systematic decision-making for centralized, distributed, and mobile biofuel production using mixed integer linear programming (MILP) under uncertainty

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Biomass resources are dispersed and subject to seasonal and geographical uncertainties. Therefore, supply chain network design and management can significantly influence the economic viability of a biofuel technology. Fast pyrolysis offers several advantages for biofuel production. It is a relatively cheap process and can be conducted in centralized, decentralizes, or even mobile configurations. Furthermore, it does not overlap with the human food supply chain, using wastes or lignocellulosic feedstocks. In this article, a mixed integer (piece-wise) linear program (MILP) was developed to determine the optimal supply chain design and operation, under uncertainty. Rigorous process modelling and detailed economic analysis were coupled with exhaustive search of potential production locations and biomass resources in order to enhance the fidelity of the solution. The optimisation results suggest that a combination of geographically centralized pyrolysis and upgrading centres would suffice for supply chain management under deterministic conditions. However, under uncertain scenarios, it is advantageous to deploy mobile pyrolyzers to add extra flexibility to the process operation. Further analysis suggested that as the mobile pyrolyzers are commercialized and their unit price is reduced, this technology has the potential to become a key member of the biofuel supply chain.

Key words:

Supply chain network; Deterministic and stochastic optimisation; Fast pyrolysis of biomass; Upgrading pyrolysis oil; Case study of biofuel production in the United Kingdom

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Introduction

Amongst various candidate conversion technologies, biomass fast pyrolysis provides the most cost-effective pathway toward biofuel production [1, 2]. However, the pyrolysis product, known as Pyrolysis Oil (PO), or bio-oil, also suffers from undesirable properties. It contains a large amount of oxygenates and has a lower heating value compared to petroleum-derived fuels. In addition, it is acidic and chemically unstable. Therefore, pyrolysis oil upgrading methods can be broadly classified into physical and chemical treatments and include filtration, solvent addition, emulsification, gasification, hydrodeoxygenation, hydrocracking and hydrothermal treatment [3]. Nevertheless, an important advantage of the pyrolysis pathway is its potential for a highly flexible operation. Pyrolysis Oil has higher energy content compared to biomass on a volume basis. It can be easily transported in liquid form and stored for short periods of time. Therefore, it is possible to build pyrolysis centres near large biomass resources and deliver the pyrolysis oil to upgrading centres. Furthermore, due to the emergence of small-scale skid-mounted pyrolyzers, it is possible to exploit small scale and disperse biomass resources and produced pyrolysis oil remotely at lower costs. Finally, unlike first generation biofuel supply chain (e.g., ethanol from sugar cane), the pyrolysis supply chain does not necessarily overlap with the human food supply chain.

Recently, Sharifzadeh, et al. [4] studied two pyrolysis oil upgrading technologies, hydrothermal upgrading (HTU) and hydrodeoxygenation (HYD) using nanocatalysts. They observed that in both scenarios, the product of short-residence time upgrading separates to aqueous and organic phases. However, the separated phases have different potentials for fuel production and hydrogen production. Based on a series of preliminary studies and key process indicators, they proposed an integrated scheme which exploits the synergies between HTU and HYD technologies. Detailed process modelling and techno-economic analysis showed that biofuel can be produced at competitive prices while the overall process is self-sustained with respect to the required hydrogen. In a separate study, Sharifzadeh, et al. [5] investigated the carbon footprint of biofuel production through biomass pyrolysis. The research importance is due to the fact that various types of biomass contain large quantities of oxygenates. For example, the effective hydrogen to carbon ratio (defined as (H-2×O)/C) of hybrid polar ($C_{4.1916}$ $H_{6.0322}$ $O_{2.5828}$) is as low as 0.207. By comparison similar value for octane (C_8H_{18}), a representative component of gasoline, is 2.25. As a result, application of biomass for producing biofuel can result in large CO_2 emissions. For example, in the pyrolysis pathway from each two carbon atoms in the biomass almost one of them (45% according to [6]) ends up in the atmosphere as CO_2. Therefore, CO2 capture and utilization should be an indispensable element of future biorefineries. In [5], Sharifzadeh and co-workers proposed an integrated scheme where the CO_2 produced during biomass pyrolysis and upgrading was captured and utilized for microalgae cultivation via photosynthesis process. Then, the cultivated microalgae biomass is used for additional fuel production. It was shown that in the new integrated refinery, the CO_2 emissions is reduced from 45% to only 6%. Furthermore, under certain economic assumptions, the extra produced fuel compensates the costs of CO_2 capture and utilization. Nevertheless, pyrolysis oil is a rich source of hydrocarbons and can be used for producing olefins and aromatics. Sharifzadeh et al., [7] in a separate study showed that it is possible to retrofit an existing olefin process using multi-stage catalytic upgrading of biomass pyrolysis oil. Detailed technoeconomic analysis as well as environmental assessment suggested that the greenhouse gas emissions are up to 44% less than conventional olefin processes, and the produced biochemical are economically competitive. Nevertheless, the research into biomass pyrolysis is inherently multidisciplinary and multiscale. It starts from the molecular scale through characterization of pyrolysis oil [8-11] and kinetic studies [12, 13]. Then, in transition from chemistry to engineering, various aspects of biomass pyrolysis such as computational fluid dynamics and design of new reactors [14-17], yield optimisation [4, 18], process intensification [19], techno-economic analysis [4, 5, 7, 20, 21] and environmental assessment [5, 7, 22] are under investigation. Finally, the overall fuel economy strongly depends on the biofuel supply chain [23-25] which is also the focus of the present research. Comprehensive reviews of biomass pyrolysis technologies are provided in [26-29]. Extensive analysis and critical reviews of supply chain design and optimisation methods are presented in [29-34].

The significance of biofuel supply chain management is due to biomass resources being geographically dispersed and the biomass supply is subject to temporal and geographical uncertainties. In many cases, feedstock location, processing sites and product destinations have profound implications for the profitability and environmental impacts of the overall biofuel supply chain. The methods for supply chain management can be broadly classified into mathematical programming and simulation studies [30]. The developed mathematical programs are concerned with optimisation of high level decisions such as supply chain configurations in additional to production and distribution planning and varies greatly with respect to the biomass type (*e.g.*, corn, wood), supply chain structure (divergent, convergent, multi-nodal), objective function (profitability, environmental implications), model type (MINLP/MILP, multi-period), and decision variables (strategic, tactical, and operational). Simulation-based studies however, focus on more detailed dynamic operation and control of fixed configurations [32, 35].

Biomass supply strongly depends on the availability of biomass resources (*e.g.*, forest, agriculture), and harvesting schemes. Therefore, regional studies have been conducted by various researchers [36-41]. Furthermore, transportation of biomass can incur high costs due to dispersed resources and low energy content. Therefore, it is often necessary to establish a compromise between the location of facilities, transportation costs and the extent of biomass pre-treatment [42, 43]. Another trade-off is observed between the centralized, decentralized and mobile production strategies. Centralized production often requires fewer and larger processing sites benefiting from economies of scale, but it also implies higher transportation costs. In a decentralized supply chain network, the processing facilities are smaller and located closer to biomass resources. Therefore, more production sites are needed. A strategy, which is less studied, is mobile production, where small-scale skid-mounted facilities are sent to remote biomass resources to benefit from cheap feedstock. In addition, it is widely observed that deterministic supply chain management can result in overoptimistic results. Using average values of biomass availability and price, product demand and incentives/tax policies may result in lower profitability or higher costs. Often a two-stage resources-base stochastic optimisation is programmed, in which long-term design decisions (*e.g.*, constructing processing facilities) are made in advance and the role of short-term operational decisions (*e.g.*, processed materials) is to counteract or take advantage of the realization of uncertain parameters [31]. Finally, the environmental implications of biofuel production should be considered in an integrated framework, where the reduced emissions due to the application of biomass are considered in conjunction with carbon dioxide and other greenhouse gases, emitted during upstream harvesting, handling, and transportation [43].

In the present research we study the design and operation of biomass pyrolysis supply chain. A multi-scale multi-period mixed integer (piece-wise) linear formulation was programmed that includes the strategic, tactical and operational decisions regarding a multinodal supply chain for production of biofuel (gasoline/diesel) compatible with current energy infrastructure. The considered production strategies include centralized, decentralized, and mobile fast pyrolysis. The aim is to study the performance of this technology and its commercial potentials. The rest of the paper is organized as follows. Firstly, the research methodology is presented and the mathematical model is explained. Then a demonstration case study for producing gasoline and diesel from lignocellulosic feedstock in the United Kingdom is formulated and solved. The case study includes both a deterministic scenario and a scenario where the biomass price and demand are uncertain. Finally the research results are presented and discussed; the features of interest include the economic performance of the deterministic and stochastic scenarios and prospective scenario for application of mobile pyrolyzers.

Methodology

The applied methodology was based on mixed integer linear programing. A multi-scale superstructure of the biofuel supply chain was developed which enabled systematic decision-making regarding three different production strategies: (1) *Centralized* processing strategy where biomass pyrolysis and upgrading are conducted at the same location, (2) *Decentralized* processing strategy where biomass pyrolysis is conducted at a separate pyrolysis plant and the pyrolysis oil is transferred to the upgrading centres, and (3) *Remote* processing strategy where pyrolysis oil produced by the mobile pyrolyzers is sent to upgrading centres for biofuel production. The trade-off between these strategies lies in the different transportation and production cost of the materials. In the first strategy, the production costs are low due to economies of scale. By comparison, in the second and third strategies, the transportation costs are minimized since pyrolysis oil is a more energy-dense fuel compared to biomass. In this research, two different types of biomass suppliers were investigated. The biomass from the first type of suppliers is available at commercial scales and can be transported efficiently only in large quantities, which is appropriate for large scale pyrolysis plants. However, the biomass from the second type of supplier is available at smaller quantities, and while is sold at a cheaper price, it also implies higher transportation distances because these suppliers are geographically dispersed. Therefore, this type of biomass resources was considered for *remote production* of biofuel using mobile pyrolyzers. Both deterministic and stochastic biofuel production was studied. While the deterministic problem provides a baseline and upper bound on the supply chain performance, the stochastic study provides an evaluation of the supply chain performance in the presence of uncertainties in consumer demands and biomass availability.

Systematic decision-making regarding strategies 1-3 requires detailed modelling of economic performance. To this end, process models were developed in Aspen Plus which enabled accurate evaluation of mass and energy balances at different production scales. This along with information regarding the equipment size was applied in order to evaluate the required investment and operating costs of the production strategies. The net present value of candidate supply chain configurations was the aggregated value of discounted cash flows of production steps in that configuration. The original Aspen plus process models and their economic models were nonlinear. In order to integrate this model into the supply chain model, a surrogate piece-wise linear economic model was developed and embedded in the supply chain model. The linearization was conducted on the equipment and operating costs and the piece-wise linear models were embedded in an economic model which evaluates the performance of the supply chain along its life-cycle.

Optimisation programming

The optimisation problem was programmed as a mixed integer linear program (MILP), implemented in GAMS and was solved with CPLEX 12.1.0 [44]. The binary variables indicated the existence or not of the processing nodes, i.e. fast pyrolysis plants, pyrolysis upgrading plants and mobile pyrolyzers, and the continuous variables characterized the flow rates of materials between the nodes, as well as the variables of the economic model. The details of the adopted notation can be found in the nomenclature.

Optimisation objective function

In the present research, the total supply chain net present value (SCNPV) was considered as the objective function (Eq. 1).

$$SCNPV = \sum_{sc} TNPV_{sc} \times PR_{sc} \qquad (1)$$

In the equation above, the objective value was characterised as the summation of the total net present value in each scenario multiplied by the probability of that scenario. A recourse-based two-stage optimisation method was applied in which the first-stage decisions variables such as the number, type, location and size of the processing plants and mobile pyrolyzers were optimised in the first stage. Then, the second-stage decisions such as flow rates of materials (biomass, pyrolysis oil and fuel) as well as relocation of mobile pyrolyzers were employed as recourse or to take advantage of realization of uncertainties. In Equation 1, the deterministic

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scenario is a particular case of the stochastic scenario, characterised with a single scenario with a probability of 100%.

Optimisation constraints: mass balances

The mass balances are enforced at each node at all time periods, as follows:

$$\sum_{u} FPU_{fp,u,t,sc} = \sum_{s} FSP_{s,fp,t,sc} \times cf_{b,o} \qquad \forall fp, sc, t \qquad (2)$$

$$\sum_{c} FUC_{u,c,t,sc} = \left(\sum_{fp} FPU_{fp,u,t,sc} + \sum_{mp} FMPU_{mp,u,t,sc}\right) \times cf_{o,gd} \qquad \forall u, sc, t \qquad (3)$$

$$\sum_{u} FMPU_{mp,u,t,sc} = \sum_{s} FSMP_{s,mp,t,sc} \times cf_{b,o} \qquad \forall mp, sc, t \qquad (4)$$

$$UND_{sc,c} \times \sum_{u} (FUC_{u,c,t,sc}) = D_{c,t,sc} \qquad \forall c, sc, t \qquad (5)$$

$$UNA_{sc} \times \sum_{fp} FSP_{s,fp,t,sc} \leq AV_s^{st1} \qquad \forall s, sc, t \qquad (6)$$

$$\sum_{mp} FSMP_{s,mp,t,sc} \leq AV_s^{st2} \qquad \forall s, sc, t \qquad (7)$$

The equality constraints 2-4 above ensure the mass balances on the fast pyrolyzer, mobile pyrolyzer and upgrading plants, respectively. Equality constraint 5 ensures that the consumers' demands are met. The last two inequality constraints 6 and 7 represent the availability of biomass resources of type 1 and 2 for large scale plants and mobile pyrolyzers respectively. The availability of large scale biomass resources and the consumers' demand were considered to be uncertain, represented by UNA_{sc} and $UND_{sc,c}$ respectively.

Optimisation constraints: fast pyrolysis and upgrading plant costs

The equipment cost is function of the plant production throughput. The equipment cost function is an exponential expression that was piece-wise linearized in order to avoid the nonlinearities (Eq. 8 and 9). To linearize the equipment cost function, the production rate was divided into small and large ranges, corresponding to small and large plants (Eq. 10 and 11). In these Equations, the index 1 refers to the range for small processes and the index 2 refers to the range for large processes. Equation 12 ensures that only one of these ranges is selected for each process, and Equations 13 to 18 introduced the upper and lower bounds of the intervals. Figure 1 illustrates the discretization of a non-linear cost function into two linear expressions.

$$EC^{fp} \geq \sum_{u} FPU_{fp,u,sc,t} \times SLP1_{fp} + INP1_{fp} \times \ y1^{fp}_{sc,t}$$

$$+ \sum_{u} FPU_{fp,u,sc,t} \times SLP2_{fp} + INP2_{fp} \times \ y2^{fp}_{sc,t} \qquad \forall fp, sc, t \qquad (8)$$

$$EC^{u} \geq \sum_{c} FUC_{u,c,sc,t} \times SLU1_{u} + INU1_{u} \times \ y1^{u}_{sc,t}$$

$$+ \sum_{c} FUC_{u,c,sc,t} \times SLU2_{u} + INU2_{u} \times y1^{u}_{sc,t} \qquad \forall u, sc, t \qquad (9)$$

$$FPU_{fp,u,t,sc} = FPU1_{fp,u,t,sc} + FPU2_{fp,u,t,sc} \qquad \forall fp, u, sc, t \qquad (10)$$

$$FUC_{u,c,t,sc} = FUC1_{u,c,t,sc} + FUC2_{u,c,t,sc} \qquad \forall u, c, sc, t \qquad (11)$$

$$y^{fp,u} = y1^{fp,u}_{sc,t} + y2^{fp,u}_{sc,t} \qquad \forall fpu, sc, t \qquad (12)$$

$$\sum_{u} FPU1_{fp,u,t,sc} \leq SCLP \times y1^{fp}_{sc,t} \qquad \forall fp, sc, t \qquad (13)$$

$$\sum_{c} FUC1_{u,c,t,sc} \leq SCLU \times y1^{u}_{sc,t} \qquad \forall u, sc, t \qquad (14)$$

$$\sum_{u} FPU2_{fp,u,t,sc} \geq SCLP \times y2^{fp}_{sc,t} \qquad \forall fp, sc, t \qquad (15)$$

$$\sum_{c} FUC2_{u,c,t,sc} \geq SCLU \times y2^{u}_{sc,t} \qquad \forall u, sc, t \qquad (16)$$

$$\sum_{u} FPU1_{fp,u,t,sc} \geq mSCLP \times y1^{fp}_{sc,t} \qquad \forall fp, sc, t \qquad (17)$$

$$\sum_{c} FUC1_{u,c,t,sc} \geq mSCLU \times y1^{u}_{sc,t} \qquad \forall u, sc, t \qquad (18)$$

FIGURE 1 HERE

Optimisation constraints: total capital investment

The economic evaluation model was developed following the method of percentage of delivered equipment costs [45]. In this method, the fixed capital investment (FCI) for each plant is a function of the direct and indirect costs; whole components in turn are estimated as the percentages of the delivered equipment costs. The required percentages are adapted from Table 6-9 of that publication for the case of solid-liquid processing plant, as shown in Table 2 and discussed later. The calculated total equipment costs (Table S1 and S2) are listed in the ESM for different scales.

The land cost (L) and the capital to depreciation (DP) are functions of the plants' throughputs. FCI for each plant is a function of the equipment cost and the direct and indirect cost factors (dcf, icf). The working capital (WC), depends on the working capital factor (wcf) and on the total capital investment (TCI), which is a function of FCI. Finally, the projected fixed capital investment ($aFCI$) takes into account the time of plant construction, and considers an investment spread over the same period. These are expressed as the Equations 19 – 24.

$$DP^{fp,u,mp} = df^{fp,u,mp} \times EC^{fp,u,mp} \qquad \forall fp, mp, u \qquad (19)$$

$$L^{fp,u,mp} = lf^{fp,u,mp} \times EC^{fp,u,mp} \qquad \forall fp, mp, u \qquad (20)$$

$$FCI^{fp,u,mp} = (dcf^{fp,u,mp} + icf^{fp,u,mp}) \times EC^{fp,u,mp} \qquad \forall fp, mp, u \qquad (21)$$

$$TCI^{fp,u,mp} = \frac{FCI^{fp,u,mp}}{tcif^{fp,u,mp}} \qquad \forall fp, mp, u \qquad (22)$$

$$WC^{fp,u,mp} = wcf^{fp,u,mp} \times TCI^{fp,u,mp} \qquad \forall fp, mp, u \qquad (23)$$

$$aFCI^{fp,u,mp} = \sum_t FCI^{fp,u,mp} \times fcif_t^{\,fp,u,mp} \times (1 + cir)^{t+2} \qquad \forall fp, mp, u \qquad (24)$$

Optimisation constraints: operating costs

The value of product (vp) depends on the product selling price (sp) and its rate of production (Eq. 25 - 27). The cost of raw materials (CRM) included natural gas (for hydrogen production), different catalysts required in the process, ash disposal, and biomass purchase. In Equations (28 - 30), (RMC) is the cost of raw materials for fast pyrolysis, upgrading and mobile pyrolysis processes, and (bC) is the cost of biomass.

$$vp_{sc,t}^{fp} = sp^{fp} * \sum_u FPU_{fp,u,sc,t} \qquad \forall fp, sc, t \qquad (25)$$

$$vp^{mp}_{sc,t} = sp^{mp} * \sum_{u} FMPU_{mp,u,sc,t} \qquad \forall mp, sc, t \qquad (26)$$

$$vp^{u}_{sc,t} = sp^{u} * \sum_{c} FUC_{u,c,sc,t} \qquad \forall u, sc, t \qquad (27)$$

$$CRM^{fp}_{sc,t} = (RMC^{fp} + bC * UNA_{sc}) \times \sum_{u} (FPU_{fp,u,sc,t}) \qquad \forall fp, sc, t \qquad (28)$$

$$CRM^{u}_{sc,t} = RMC^{u} \times \sum_{c} (FUC_{u,c,sc,t}) \qquad \forall u, sc, t \qquad (29)$$

$$CRM^{mp}_{sc,t} = RMC^{mp} \times \sum_{u} (FMPU_{mp,u,sc,t}) \qquad \forall mp, sc, t \qquad (30)$$

The operating labour (OL) is function of the number of workers at each plant, which depends on the plant production rate (Equations 31 - 33). Moreover, the costs of utilities (UT), which includes cooling water, electricity, and steam, are proportional to the plant production rate (Equations 34 - 36). The variable cost (VC) is the summation of the labour costs, the utility costs, the raw material costs and the plant insurance (Eq. 37). Finally, the total production cost $TPC^{fp,u,mp}_{sc,t}$ is the summation of the variable cost, the repairs and maintenance of each plant, the transportation costs (discussed later), and the salary of the truck drivers and the rental price of the trucks (Eq. 38).

$$OL^{fp}_{sc,t} = olf^{fp} \times \sum_{u} FPU_{fp,u,sc,t} \qquad \forall fp, sc, t \qquad (31)$$

$$OL^{u}_{sc,t} = olf^{u} \times \sum_{c} FUC_{u,c,sc,t} \qquad \forall u, sc, t \qquad (32)$$

$$OL^{mp}_{sc,t} = olf^{mp} \times \sum_{u} FMPU_{mp,u,sc,t} \qquad \forall mp, sc, t \qquad (33)$$

$$UT^{fp}_{sc,t} = utf^{fp} \times \sum_{u} FPU_{fp,u,sc,t} \qquad \forall fp, sc, t \qquad (34)$$

$$UT^{u}_{sc,t} = utf^{u} \times \sum_{c} FUC_{u,c,sc,t} \qquad \forall u, sc, t \qquad (35)$$

$$UT^{mp}_{sc,t} = utf^{mp} \times \sum_{u} FMPU_{mp,u,sc,t} \qquad \forall mp, sc, t \qquad (36)$$

$$VC^{fp,u,mp}_{sc,t} = OL^{fp,u,mp}_{sc,t} \times smr^{fp,u,mp} + UT^{fp,u,mp}_{sc,t} + CRM^{fp,u,mp}_{sc,t} \qquad \forall fp, u, mp, sc, t \qquad (37)$$

$$TPC^{fp,u,mp}_{sc,t} = VC^{fp,u,mp}_{sc,t} + aFCI^{fp,u,mp} * ti^{fp,u,mp} + TC^{fp,u,mp}_{sc,t} + TT^{fp,u,mp}_{sc,t} \times (LD + RP) \qquad \forall fp, u, mp, sc, t \qquad (38)$$

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The annual gross profit (AGP) is the difference between the projected revenues and the total production cost, depreciation cost and the start-up costs (Equation 39). The annual gross profits of each process are added together to calculate the total annual gross profit (Equation 40). The total annual net profit ($TANP$) is calculated by deducing the taxes from the total annual gross profit (Equation 41). The total annual operating cash flow ($TAOCF$) is obtained by adding the depreciation costs to the total annual net profit (Equation 42). The total annual cash flow ($TACF$) is total annual operating cash flow minus the investments that are needed for working capital investments, land price, and fixed capital investments (in the construction only) (Equation 43). Finally, the total net present value is obtained by adding all the $TACF$ multiplied by the present worth factor (pwf) (Equation 44).

$$AGP_{sc,t}^{fp,u,mp} = vp_{sc,t}^{fp,u,mp} \times (1+PIR)^{2+t} - TPC_{sc,t}^{fp,u,mp} \times (1+TPCir)^{2+t} - df \times DP^{fp,u,mp} - SU \qquad \forall fp,u,mp,sc,t \qquad (39)$$

$$TAGP_{t,sc} = \sum_{fp,u,mp} AGP_{sc,t}^{fp,u,mp} \qquad \forall sc,t \qquad (40)$$

$$TANP_{t,sc} = TAGP_{t,sc} \times (1 - tax) \qquad \forall sc,t \qquad (41)$$

$$TAOCF_{t,sc} = TANP_{t,sc} + df_t \times \left(\sum_{fp,u,mp} DP^{fp,u,mp} \right) \qquad \forall sc,t \qquad (42)$$

$$TACF_{t,sc} = TAOCF_{t,sc} - \sum_{fp,u,mp} FCI^{fp,u,mp} \times fcif_t^{\ fp,u,mp} - \sum_{fp,u} L_t^{fp,u} - \sum_{fp,u,mp} WC_t^{fp,u,mp} \qquad \forall sc,t \qquad (43)$$

$$TNPV_{sc} = \sum_t (TACF_{t,sc} \times pwf_t) \qquad \forall sc \qquad (44)$$

Optimisation constraints: transportation costs

The transportation costs (TC) depend on the amount of transported materials (biomass, pyrolysis oil, fuel), the unit transportation cost of each material and the distance (DS) between two nodes. The trucks necessary to transport all the materials (TT) are integer numbers, and are function of the distance between two nodes, the amount of material to transport, the capacity of the trucks (CT), the average velocity of the trucks (VL), the number of working hours per day of a truck driver (WH) and the working days per year (DY), (Equations 45 – 50).

$$TC_{sc,t}^{fp} = \sum_{s} \left(DS \times FSP_{s,fp,sc,t} \times tcf_b \right) + \sum_{u} \left(DS * FPU_{fp,u,sc,t} \times tcf_o \right) \qquad \forall fp, sc, t \qquad (45)$$

$$TC_{sc,t}^{u} = \sum_{c} (DS \times FUC_{u,c,sc,t} \times tcf_{gd}) \qquad \forall u, sc, t \qquad (46)$$

$$TC_{sc,t}^{mp} = \sum_{u} \left(DS \times FMPU_{mp,u,sc,t} \times tcf_o \times cfo \right) \qquad \forall mp, sc, t \qquad (47)$$

$$TT_{sc,t}^{fp} \geq \sum_{s} (DS \times \frac{FSP_{s,fp,sc,t}}{CT_b * VL * WH * DY}) + \sum_{u} (DS \times \frac{FPU_{fp,u,sc,t}}{CT_o * VL * WH * DY}) \qquad \forall fp, sc, t \qquad (48)$$

$$TT_{sc,t}^{mp} \geq \sum_{u} (DS \times \frac{FMPU_{mp,u,sc,t}}{CT_o * VL * WH * DY}) \qquad \forall mp, sc, t \qquad (49)$$

$$TT_{sc,t}^{u} \geq \sum_{c} (DS \times \frac{FMPU_{u,c,sc,t}}{CT_{gd} * VL * WH * DY}) \qquad \forall u, sc, t \qquad (50)$$

Optimisation constraints: transportation distance

The distance between any two points was calculated using the Haversine formula [46] (Equation 51). The required information in this formula is the geographical coordinates of the two points: latitude and longitude. In addition, the distance was corrected with the tortuosity factor (τ), which accounts for curvatures on the roads. The recommended values for the tortuosity factor are between 1.2 and 3, and in the present research the value of 1.5 was chosen.

$$DS_{i,j} = \tau \times 2\, \xi \arcsin\left(\sqrt{sin^2\left(\frac{\emptyset_i - \emptyset_j}{2}\right) + cos(\emptyset_i)\, cos(\emptyset_j)\, sin^2\left(\frac{\lambda_i - \lambda_j}{2}\right)} \right) \qquad (51)$$

Where the subindexes i and j make reference to the destination and origin respectively.

Optimisation constraints: mobile pyrolysis costs

The equipment cost of a mobile pyrolyzer was fixed at 3.60 M$ for each unit according to [47]. However, in order to investigate perspective scenarios for commercialization of this technology, a sensitivity analysis was also conducted, and the impact of mobile pyrolysis price on its potential exploitation within a flexible supply chain was studied under stochastic scenarios. The mobile pyrolyzers operate for a maximum of 330 days per year. For utilization, mobile pyrolyzers should be sent to remote locations. The relocation time is 10 days and the relocation cost is 680 $ [47]. The corresponding constraints are shown below (Equations 52 – 60).

$$EC^{mp} = MPP \times y^{mp} \quad \forall mp \quad (52)$$

$$FSMP_{s,mp,sc,t} \leq AV_s^{st2} \times ymp_{s,mp,sc,t} \quad \forall s, mp, sc, t \quad (53)$$

$$rc_{s,mp,sc,t} = rcf \times ymp_{s,mp,sc,t} \quad \forall s, mp, sc, t \quad (54)$$

$$top_{mp,sc,t} = \sum_s \sum_u (FSMP_{s,mp,sc,t})/cm \quad \forall mp, sc, t \quad (55)$$

$$tum_{mp,sc,t} = 5 \times \sum_s ymp_{s,mp,sc,t} \quad \forall mp, sc, t \quad (56)$$

$$tsm_{mp,sc,t} = 5 \times \sum_s ymp_{s,mp,sc,t} \quad \forall mp, sc, t \quad (57)$$

$$time_{mp,sc,t} = top_{mp,sc,t} + tsm_{mp,sc,t} + tum_{mp,sc,t} \quad \forall mp, sc, t \quad (58)$$

$$330 \geq time_{mp,sc,t} \quad \forall mp, sc, t \quad (59)$$

$$NMP = \sum_{mp} y^{mp} \quad (60)$$

In the equations above, equality constraint (52) refers to the purchased equipment cost of mobile pyrolyzers. The decision variable $ymp_{s,mp,sc,t}$ assigns a binary value to mobile pyrolyzer mp at each type-2 biomass supplier s, at time t, and scenario sc. Inequality (7) poses an upper bound on the maximum biomass that each type-2 supplier can provide. Inequality constraint (53) ensures that if a mobile pyrolyzer is not sent to a supplier the associated flow of biomass is zero. Equation (54) is used to assign the relocation cost of the mobile pyrolyzers. Equation (55) ensures that sufficient operating time is allocated to each mobile pyrolyzer for processing the biomass purchased at each type-2 supplier. In Equation 56, $tum_{mp,sc,t}$ is the time needed to disassemble the mobile pyrolyzer, mp, for all type-2 suppliers associated with that mobile pyrolyzer in all time intervals for each stochastic scenario. Similarly, $tsm_{mp,sc,t}$ refers to assembling time needed for each mobile pyrolyzer (Equation 57). The operating time and the settling and dismantling times are added to calculate the total time in days, and this has to be less than or equal to the number of working days per year (Equations 58 and 59). Finally, the total number of mobile pyrolyzers is the addition of all mobile pyrolyzers purchased (Equation 60).

Case study description

The present case study aims at developing a cost-efficient supply chain for two consumption areas: one in London and the other in the metropolitan area of Liverpool in the United Kingdom. The considered throughput was the total of 290 dam^3 of gasoline and diesel per annum which is equivalent to 2 Gg d^{-1} of dry biomass. Figure 2 shows the suppliers and processing sites considered in the present study, which included six suppliers of the first type [48], fifteen suppliers of the second type [48], and six potential processing centres. Such a super-structure provided a flexible framework for the optimisation algorithm to choose between the following production strategies: (1) centralized processing where biomass pyrolysis and upgrading are conducted at the same place, (2) decentralized processing where biomass pyrolysis is conducted at a distant pyrolysis plant and the pyrolysis oil is transferred to upgrading centres, and (3) remote production where pyrolysis oil produced by the mobile pyrolyzers is sent to upgrading centres for biofuel production. In the following, the corresponding instance of the aforementioned mathematical formulation and underlying assumptions for the case of biofuel production from lignocellulosic feedstocks in the UK are elaborated and justified.

FIGURE 2 HERE

Processing plants: fast pyrolysis and pyrolysis oil upgrading

The most significant reactions are fast biomass pyrolysis and pyrolysis oil upgrading. The fast pyrolysis of biomass is typically conducted in a circulating fluidized bed which is the most promising configuration for scale up [6]. For small scale mobile pyrolyzers simpler configurations such as augers or moving bed reactors are favourable [47]. Pyrolysis upgrading technology adapted in this publication was based on previous research by DOE [6] and consisted of two-stage stabilization and upgrading followed by separation and hydrocracking of heavy ends. Table 1 reports the conversion factors of these reactions. Here, the gasoline and diesel fuels are aggregated as the general term of “Biofuel” based on a constant ratio of 43/57 mass basis.

TABLE 1 HERE

In order to estimate the total capital investment of each processing plant (fast pyrolysis and pyrolysis oil upgrading) and embed that in the overall supply chain economic model, it is necessary to represent the purchased equipment costs as a function of process throughput. To this end, firstly, process models were developed for all the processing sections and were validated according to the benchmark results from [6]. Then, the process models were scaled to different throughputs and corresponding equipment costs were fitted to the following piece-wise linear cost functions (Equations 61 and 62):

Fast pyrolysis:

$$y = 0.0145x + 2.4692 \qquad 200 \le x \le 850 \qquad (61A)$$

$$y = 0.0105x + 5.8275 \qquad 850 < x \leq 2000 \qquad (61B)$$

Upgrading:

$$y = 0.0259x + 18.1090 \qquad 200 \leq x \leq 850 \qquad (62A)$$

$$y = 0.0189x + 23.9993 \qquad 850 < x \leq 2000 \qquad (62B)$$

In the equations above x is the plant capacity in Mg d^{-1} of biomass, and y is the total cost of purchased equipment in M$ in the two different sections. In constructing the meta-model above, the exponential correlation showed in Equation 63 was considered [45]:

$$Cost_{size2} = Cost_{size1} * \left(\frac{capacity_{size2}}{capacity_{size1}}\right)^n \qquad (63)$$

The detailed list of equipment with individual prices is presented in the ESM. Then, the total equipment cost at every scale is the summation of all the equipment cost at each scale and a contingency factor (35% for the fast pyrolysis equipment and 15% for the pyrolysis oil upgrading equipment), [6]. It was also assumed that the reaction yields do not depend on the equipment costs. The maximum scale value was set to satisfy the total demand: 290 dam^3 y^{-1} of product, which corresponds to 2 Gg d^{-1} of dry biomass. The minimum scale was set at the 10% of the maximum scale, to account for small and distributed production processes. The intermediate scale (850 Mg d^{-1}) was optimized in order to minimize the difference between the original nonlinear cost function and the surrogate piece-wise linear model. The details of this optimisation are reported in the ESM. The individual equipment costs at every scale for the fast pyrolysis and the pyrolysis oil upgrading sections can be found in the ESM.

The economic analysis was based on the percentage of delivered equipment cost method [45]. The total capital investment (TCI) of each processing plant (fast pyrolyzer or pyrolysis oil upgrading) is a function of purchased equipment costs as outlined in Table 2.

TABLE 2 HERE

The plants are assumed to be built in 2 years, and the production starts at the beginning of the third year, which is considered to be the year 0. The plant economic life is 10 years. The fixed capital investment (FCI) is paid during the first two years of construction and at the beginning of the first year of production. The percentages of the FCI paid each year are shown in Table 3. The operating labour was calculated based on 3 working shifts per day. A total of 12 workers per shift are necessary to operate the pyrolysis oil upgrading section with a plant throughput of 2 Gg d^{-1} and 4 workers per shift were considered in the fast pyrolysis plant

[6]. The average salary for the workers in the UK is 57.678 \$ h^{-1}, [49]. The total production costs expressed as a function of the operating labour or the fixed capital investment are listed in Table 4. The variation of total utility costs with the production scale was firstly calculated using Aspen plus simulations and then a surrogate piece-wise linear model was calculated for fast pyrolysis and pyrolysis oil upgrading units. The result of the simulations can be found in the ESM. The economic values of the utilisation costs are taken from Aspen Plus, which include electricity, cooling water, three qualities of steam generation and fire heater. Finally, the feedstock costs are presented in Table 5.

TABLE 3 HERE

TABLE 4 HERE

TABLE 5 HERE

Mobile pyrolyzer costs

A mobile pyrolyzer is a small capacity fast pyrolysis plant that is portable. Its main advantage is the ability to exploit resources in different locations at low purchasing and transportation costs. Mobile pyrolyzers are still under development and there are very few industrial purchasing options [58-60]. The system referred as mobile pyrolyzer includes a pyrolysis reactor and furnace, biomass dryer, cooling tower, flex fuel generator. In the present research, the economic analysis was performed following the guidance proposed by Sorenson [47]. The system has a capacity of 50 Mg d^{-1} of dry biomass. An ablative fast pyrolyzer has been chosen for this study, and the production yields as percentage of dry biomass are summarized in Table 6. Two operators are necessary to operate the mobile pyrolyzer system [47]. To ensure a 24 hour production 3 shifts per day were chosen. A price of 25 \$ Mg^{-1} of feedstock was reported for the purchasing, piling and chipping of remote and disperse biomass, a very similar value to the forest residues in the Sarkar *et al*., study [50]. The only utility required in mobile pyrolyzers is propane to maintain the temperature at adequate levels in the reactor. The amount of propane to purchase is 263.83 m^3 y^{-1} and the propane price is 602 \$ m^{-3}. Insurance and maintenance costs are considered to be 1.25% and 0.82% of fixed capital investment respectively. The relocation cost does not depend on the distance, since the largest contributors are the costs associated with the dismantling and reassembling of the equipment, and it is fixed at 680 \$. The taxation rate and interest rates were adapted from [6].

TABLE 6 HERE

This article should be cited as: Sharifzadeh M*, Cortada Garcia M, Nilay Shah, (2015). Supply chain network design and operation: Systematic decision-making for centralized, distributed, and mobile biofuel production using mixed integer linear programming (MILP) under uncertainty. Biomass and Bioenergy, 2015, 81, 401–414, (Link).

Transportation costs

There are three materials that need to be transported: biomass, pyrolysis oil and gasoline and diesel. Only the option of road transportation was considered. Two different types of trucks were necessary: freight trucks for the transportation of solid material (biomass) and tank lorries to transport liquid materials (pyrolysis oil and gasoline and diesel). Every tank lorry was considered for only one type of fuel, either pyrolysis oil or gasoline and diesel. Table 7 shows truck capacity, fuel density and calculated costs of fuel transportation. Trucks were rented at the price of 25,000 $ y^{-1}. In addition, the average salary for a truck driver was estimated to be 40,000 $ y^{-1} [51]. The maximum number of working hours per day of a driver is 10, the number of working days per year is 254 d y^{-1} [52], and the average velocity of a truck is 45 km h^{-1} [53].

TABLE 7 HERE

Uncertainty

Table 8 shows the considered scenarios for the stochastic supply chain. Two parameters were considered to be the most uncertain: the raw material availability, due to its dependence on weather conditions, and the biofuel demand of the two consumption regions. Considering two realizations (high/low) for each uncertain parameter, the total of eight stochastic scenarios were studied. With respect to biomass availability, the low availability was considered to have a reduction of the 20% with respect to the high availability scenario. Nevertheless, the biomass price is strongly correlated to its availability. Here, it was assumed that in low availability scenarios, the biomass price would increase by 20%.

With respect to biofuel demand, 89.4 dam^3 y^{-1} in Liverpool and 200.6 dam^3 y^{-1} in London were considered high; and low demand level was assumed to be 20% less than those values. The biofuel price in all cases was at 1,541 $ m^{-3}, [56]. Finally, it was assumed that all scenarios are equally likely (even distribution).

TABLE 8 HERE

Results and discussions

The results are presented in this section. The features of interest are the supply chain geographical configurations, systematic decision-making between various strategies 1-3 (as discussed in the methodology section) and the economic performance of the optimized supply chain under deterministic and stochastic conditions.

Deterministic case

The deterministic case is characterized by the absence of uncertain variables. Figure 3 shows that the first production strategy was selected, *i.e.*, the optimal supply chain configuration is to build two large-scale centralized pyrolysis and upgrading plants at the urban area of Liverpool and the other in the metropolitan area of Bristol. The throughput of the fast pyrolysis and pyrolysis oil upgrading sections for the two processing centres is shown in Table 9. Table 10 shows both, the amount and the fraction of biomass utilized from each type-1 supplier in each processing site. Table 11 shows the amount of biofuel supplied from each processing site to the consumption areas and the percentage of the demand supplied at each consumption area.

In the deterministic scenario, two extremes were clearly avoided. One extreme was to build a single very large scale process where the implication of having high costs of biomass transportation is unjustifiable. The other extreme would be to build numerous small scale plants near biomass resources where the investment capital could be high due to the lack of economies of scale. Therefore, a compromise was established between the economies of scale and biomass transportation costs and two large scale processes where built in proximity of large scale (type-1) biomass resources.

FIGURE 3 HERE

TABLE 9 HERE

TABLE 10 HERE

TABLE 11 HERE

Stochastic case

As discussed earlier, the uncertain variables in the stochastic study were the biomass availability and consumer region demands. As shown in Table 12 and similarly to the deterministic case, the optimal decisions included constructing two processing centres with both fast pyrolysis and upgrading sections; one was located in the urban area of Liverpool and the other in the metropolitan area of Bristol. However, in the stochastic case, two mobile pyrolyzers were also selected in order to introduce flexibility into the supply chain operation. The flow rates of biomass supply (from type-1 suppliers) to the fast pyrolysis sections are shown in Table 13. In addition, the mobile pyrolyzers were exploited to benefit from the cheap and dispersed biomass resources (from type-2 suppliers), as shown in Table 14. Table 15 shows the biofuel supply to consumer regions. The plant in Liverpool satisfied all the demand in the same area and in addition supplies products to the London region. The rest of the London demand was supplied by Bristol plant. Figure 4 shows the results of the stochastic scenarios graphically.

FIGURE 4 HERE

In both deterministic and stochastic studies, two centralized (fast pyrolysis and upgrading) processing sites were built in the vicinity of the large biomass suppliers. However, the sizes of the fast pyrolysis section were smaller in the stochastic case, and the remaining production capacity was allocated to mobile pyrolyzers which could flexibly exploit cheap biomass resources. Since the price of type-2 biomass is cheaper, all of the mobile pyrolyzers' capacity was exploited in all scenarios, regardless of the performance of the uncertain variables; and in the scenarios when the biofuel demand was lower, or biomass was more expensive, the capacities of the fast pyrolysis sections were adjusted to save the unnecessary costs.

TABLE 12 HERE

TABLE 13 HERE

TABLE 14 HERE

TABLE 15 HERE

Economic evaluation

Figure 5 shows the cumulative cash position curves for stochastic and deterministic studies. The dashed blue curve and the solid red curve refer to the deterministic and stochastic cases respectively, indicating that the break-even occurs at years 2.1 for the deterministic case, and at the 2.6 year for the stochastic case. The optimal supply chain net present values ($SCNPV$) were notably different under the presence or not of uncertainties; 1,031.50 M$ and 860.57 M$ for deterministic and stochastic respectively. The reason for the reduction in net present value was the presence of undesirable uncertainties such as unavailability of biomass near the processing locations or reduced demand. Nonetheless, the stochastic scenario provides a more realistic perspective of the actual performance of the supply chain.

FIGURE 5 HERE

Perspective scenario for mobile pyrolyzers: Sensitivity analysis

The mobile pyrolysis price is expected to drop dramatically during the next few years as it becomes a more established technology. As shown in Figure 6, in the absence of uncertainty, the mobile pyrolysis unit was not a viable option at its current price. However, in the presence of uncertainties (Figure 7), the mobile pyrolyzer even at the current high price is economic, because it can benefit from cheap type-2 biomass resources, when the type-1 biomass is expensive or unavailable. These figures also show when this technology becomes more established, and therefore its unit price is reduced, the number of mobile pyrolyzers employed increases and consequently, the overall supply chain net present value also increases.

FIGURE 6 HERE

FIGURE 7 HERE

Post-optimization analysis

The interest rate and depreciable life of plant can significantly affect the economy of the process. In order to identify the influence of these variables, a post-optimization sensitivity analysis was conducted. Figure 8 shows the results of sensitivity analysis with respect to the interest rate. It shows that as the interest rate decreases the net present value of the supply chain network increases. In addition, the interest rate for which the net present value is zero, known as "internal rate of return" was calculated to be 33% and 37% for the stochastic and deterministic cases respectively. Figure 9 shows the sensitivity of the total supply chain net present value with respect to the effective life of the mobile pyrolyzers. The study was conducted by reducing the life of the mobile pyrolyzers to a half, a third, a quarter and a fifth of the expected value (10 years, Sorenson [47]). This figure suggests that as the life of mobile pyrolyzers reduces from 10 year to 2 years, the total net present value of the supply chain reduced by 1.90 %.

FIGURE 8 HERE

FIGURE 9 HERE

Future work

The supply chain network proposed in this research is concerned with innovative technologies which are under development. There are several technoeconomic analyses in the open literature [6, 57] that show promise for commercialization of these technologies. In addition this technology is being promoted by industry [58-60]. In this research, it was shown that as the price of mobile pyrolyzers decreases, a larger number of this units could be adapted in the cost-efficient supply chain. From the feedstock viewpoint, pyrolysis technology is highly flexible as it can exploit agricultural wastes [61-63], forest residues [63, 64], and plastic wastes [65, 66]. Even co-pyrolysis of various feed stocks is reported in literature [67, 68]. However, various feedstocks can have different bio-oil yields and the produced char and biogas can be significant [26]. As a result, local generation of electricity using pyrolysis by-products can potentially improve the overall energy conversion efficiency. On the stationary pyrolysis plant, biomass pre-treatment (chemical, microbial with fungi and enzymes, fractionation using ionic liquids) can increase significantly the biomass conversion [69-74]. Nevertheless, mobile pyrolyzers relay on cheap feedstock. Therefore, developing reactors which can flexibly process or co-process various types of feeds are highly desirable.

While the present research explored the concept of flexible operation of biofuel supply chain via fast pyrolysis, further research is needed in order to investigate the operational characteristics of biofuel supply chains. Of significant research potential are the options for storing biomass in order to overcome uncertainties, other transportation modes such as pipelines and trains, and remote control and operation of mobile pyrolyzers. Nevertheless, design and control of bioprocesses are highly interconnected. Systematic methodologies for integrated design and operation of bioprocesses are highly desirable [75].

Conclusions

The present study applied mathematical programming for optimisation of a biofuel supply chain via fast pyrolysis. Various options including centralised, decentralised and mobile production strategies were considered. The formulated program was applied to the case of 290,000 m^3 biofuel per annum in the United Kingdom. It was observed that there is an important trade-off between the costs of biomass transportation and economies of scale. In addition, it was shown that in the presence of uncertainty, flexible operation of the

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supply chain has economic significance. In this context, as mobile pyrolyzers are commercialised, they will play an important role in the future of biofuel supply chain.

Nomenclature

aFCI	Actualized fixed capital investment
AGP	Annual gross profit
AV	Available biomass
b	Biomass
bC	Biomass cost
c	Consumer
cf	Conversion factor
cir	Construction inflation rate
cm	Mobile pyrolyzer capacity
CRM	Cost raw material
CT	Truck capacity
D	Distance
dcf	Direct capital factor
df	Depreciation factor
DP	Depreciation
DS	Distance
DY	Working days per year
EC	Equipment cost
FCI	Fixed Capital investment
fcif	Fixed Capital investment factor
FMPU	Flow of material between mobile pyrolysis to upgrading plants
fp	Fast pyrolysis plant
FPU	Flow of material between pyrolysis to upgrading plants
FPU1	Flow of material between small pyrolysis plants to upgrading plants
FPU2	Flow of material between large pyrolysis to upgrading plants
FSMP	Flow of material between suppliers to mobile pyrolyzers
FSP	Flow of material between suppliers to pyrolysis plants
FUC	Flow of material between upgrading plants to consumers
FUC1	Flow of material between small upgrading plants to consumers
FUC2	Flow of material between large upgrading plants to consumers
gd	Gasoline + diesel
icf	Indirect capital factor
INP1	Intercept equipment cost of pyrolysis plant vs small plant capacity
INP2	Intercept equipment cost of pyrolysis plant vs large plant capacity
INU1	Intercept equipment cost of upgrading plant vs small plant capacity
INU2	Intercept equipment cost of upgrading plant vs large plant capacity
L	Land cost
LD	Labour truck driver
lf	Land factor
mp	Mobile pyrolyzer
MPP	Mobile pyrolyzer price
mSCLP	Minimum scale pyrolysis plant
mSCLU	Minimum scale upgrading plant
n	Equipment cost scaling factor
NMP	Number of mobile pyrolyzers
o	pyrolysis oil
OL	Operating labour
olf	Operating labour factor
PIR	Product interest rate
PR	Probability
pwf	Present worth factor
rc	Relocation cost

rcf	Relocation cost factor
RMC	Raw material purchasing cost
RP	Truck rental price
s	Supplier
sc	Scenario
SCLP	Scale change from small to large in pyrolysis plants
SCLU	Scale change from small to large in upgrading plants
SCNPV	Supply Chain Net present value
SLP1	Slope equipment cost of pyrolysis plant vs small plant capacity
SLP2	Slope equipment cost of pyrolysis plant vs large plant capacity
SLU1	Slope equipment cost of upgrading plant vs small plant capacity
SLU2	Slope equipment cost of upgrading plant vs large plant capacity
smr	Supervision, maintenance and repairs
sp	Selling price
st1	Supplier type 1
st2	Supplier type 2
SU	Starting up
t	Year
TACF	Total annual cash flow
TAGP	Total annual gross profit
TANP	Total annual net profit
TAOCF	Total annual operating cash flow
tax	Taxation rate
TC	Transportation cost
tcf	Transportation cost factor
TCI	Total capital investment
tcif	Total capital investment factor
ti	Taxes and insurance
time	Total mobile pyrolyzer operating time
TNPV	Total net present value
top	Operating time
TPC	Total production cost
TPCir	Production interest rate
tsm	Settling mobile pyrolyzer time
TT	Total number of trucks
tum	Uninstalling mobile pyrolyzer time
u	Upgrading plant
UNA	Uncertainty in the availability
UND	Uncertainty in the demand
UT	Utilisation cost
utf	Utilisation cost factor
VC	Variable cost
VL	Average velocity
vp	Revenues
WC	Working capital
wcf	Working capital factor
WH	Working hours per day
y	Existence of plant
y1	Existence of small plant
$y2$	Existence of large plant
ymp	Allocation of a mobile pyrolyzer to a certain location
$\emptyset$	Longitude
λ	Latitude
τ	Tortuosity

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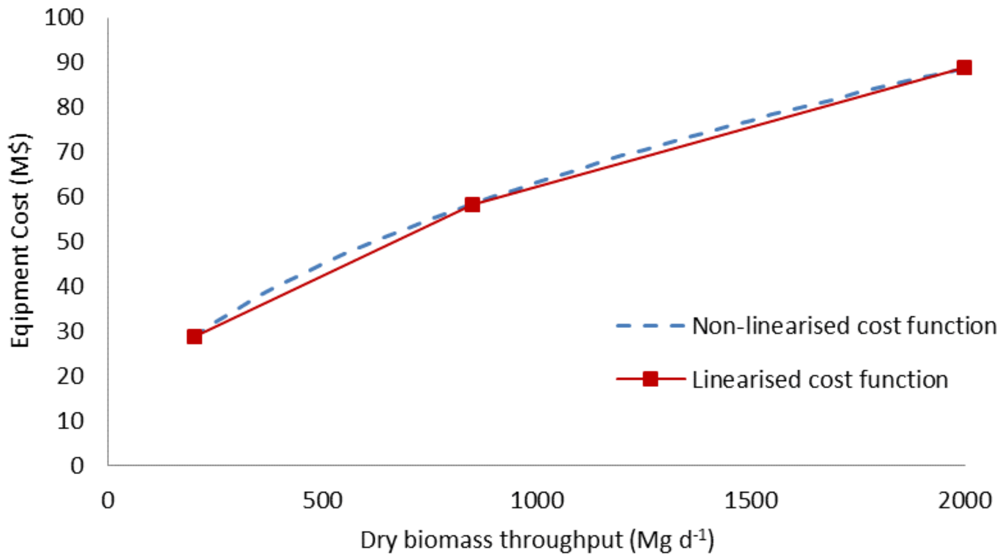

Figure 1 –Piece-wise linearization of equipment costs as the function of process throughput.

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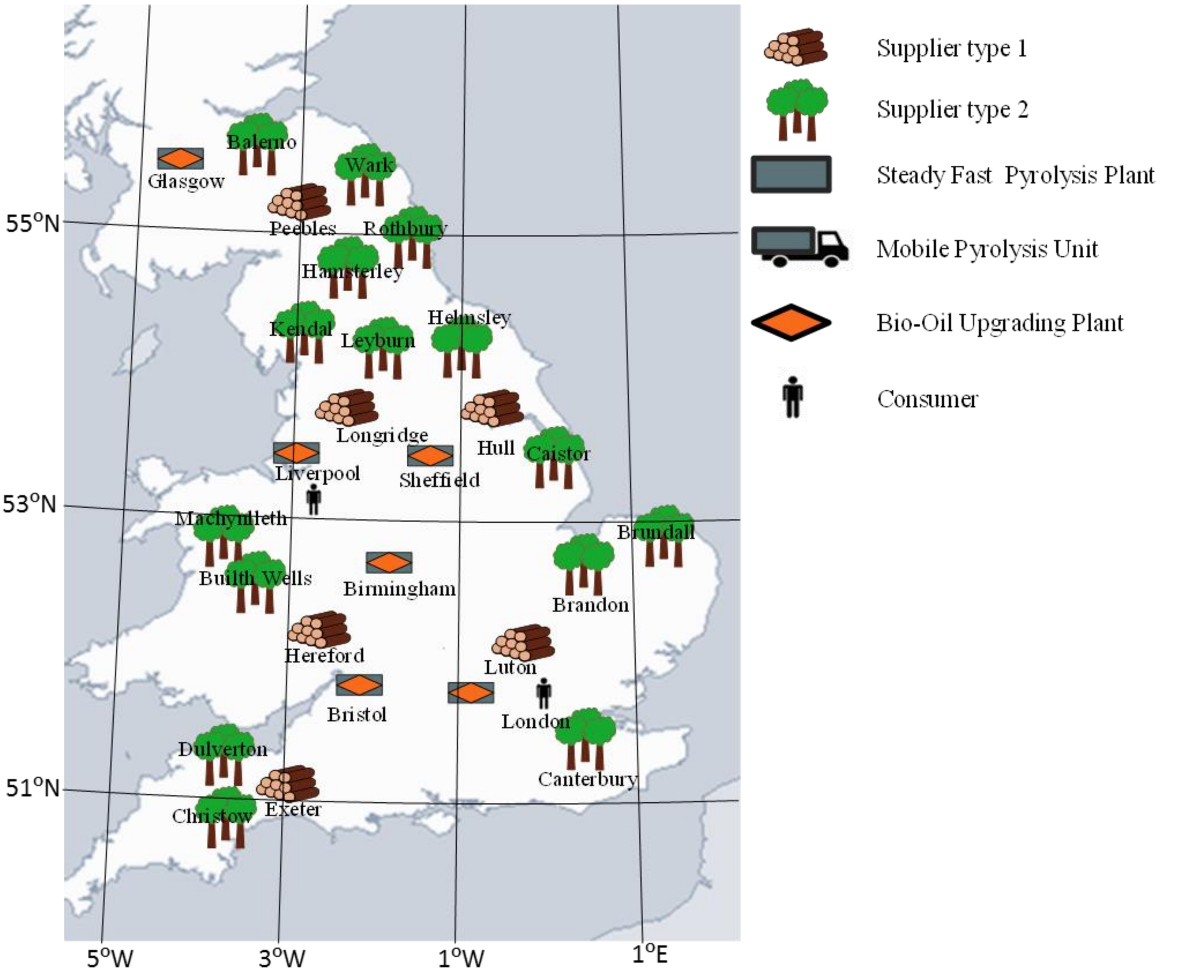

Figure 2 - The geographical position of the considered suppliers, processing sites and consumptions areas for the proposed supply chain optimisation framework.

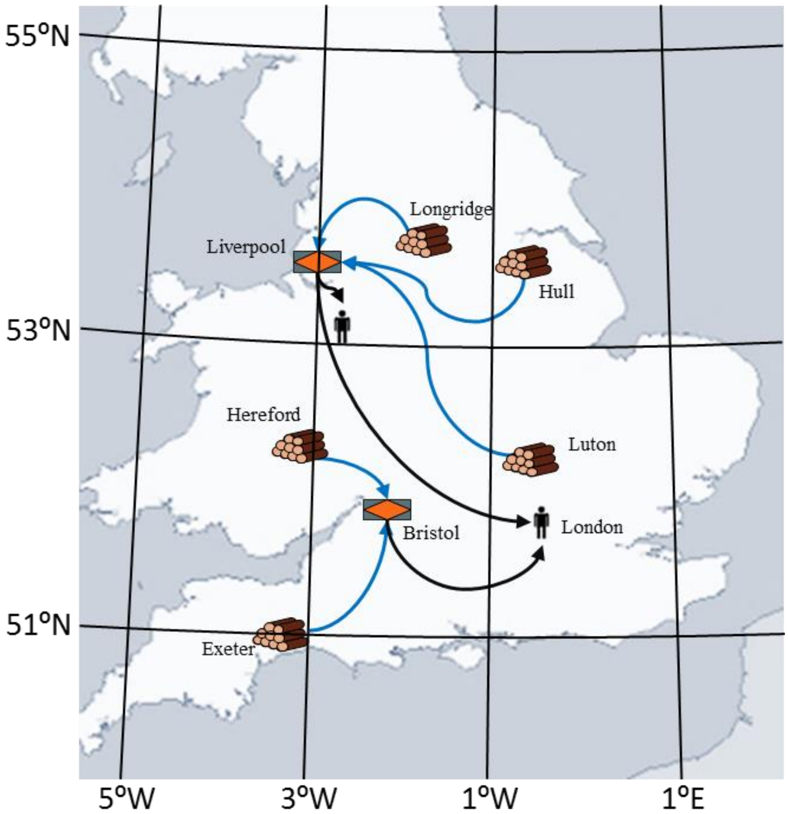

Figure 3 - Deterministic supply chain. The blue arrows represent the flow of biomass, and the black arrows refer to the flow of the fuel product (gasoline + diesel).

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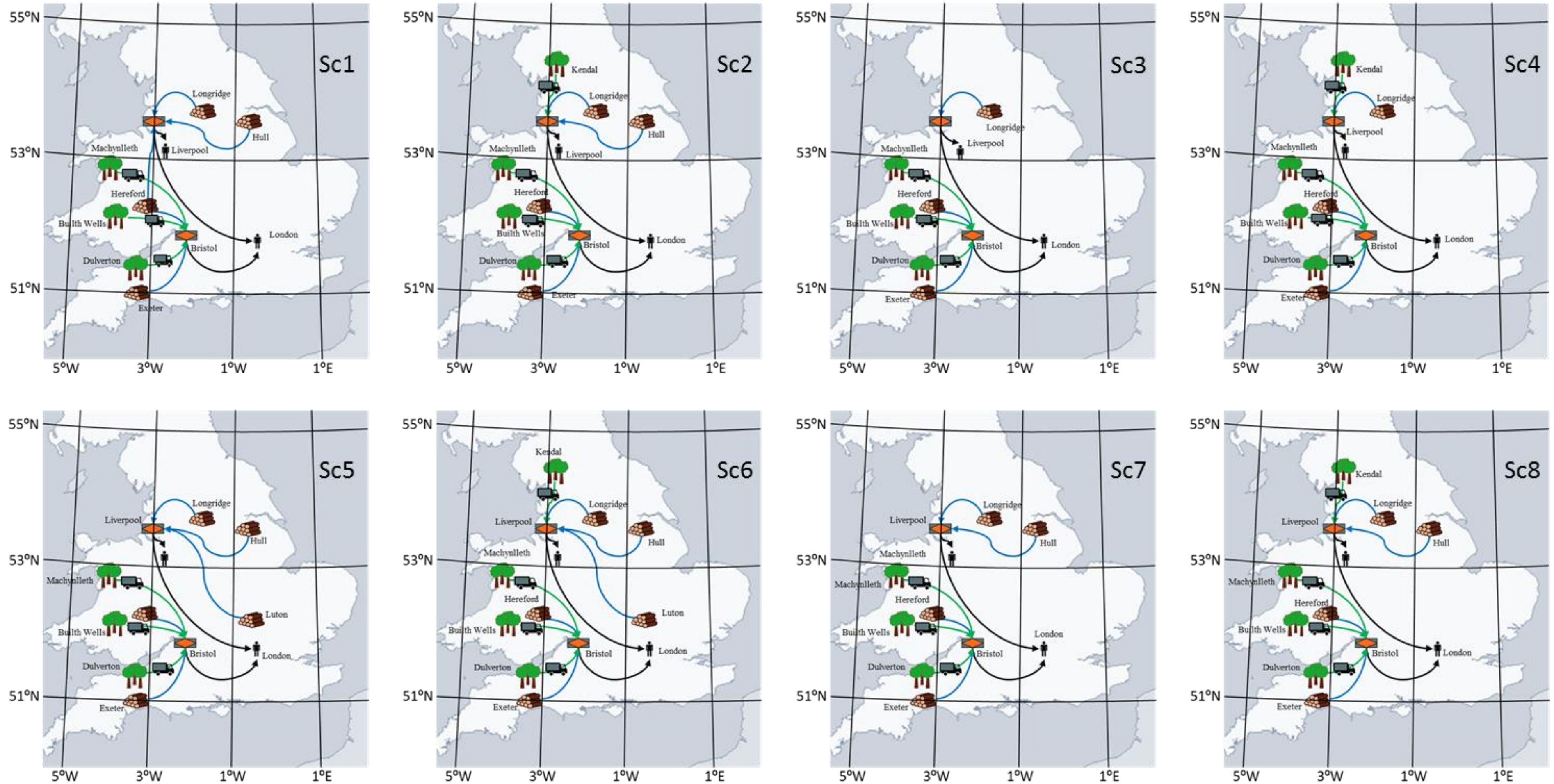

Figure 4 - Stochastic supply chain for the scenarios 1 – 8.

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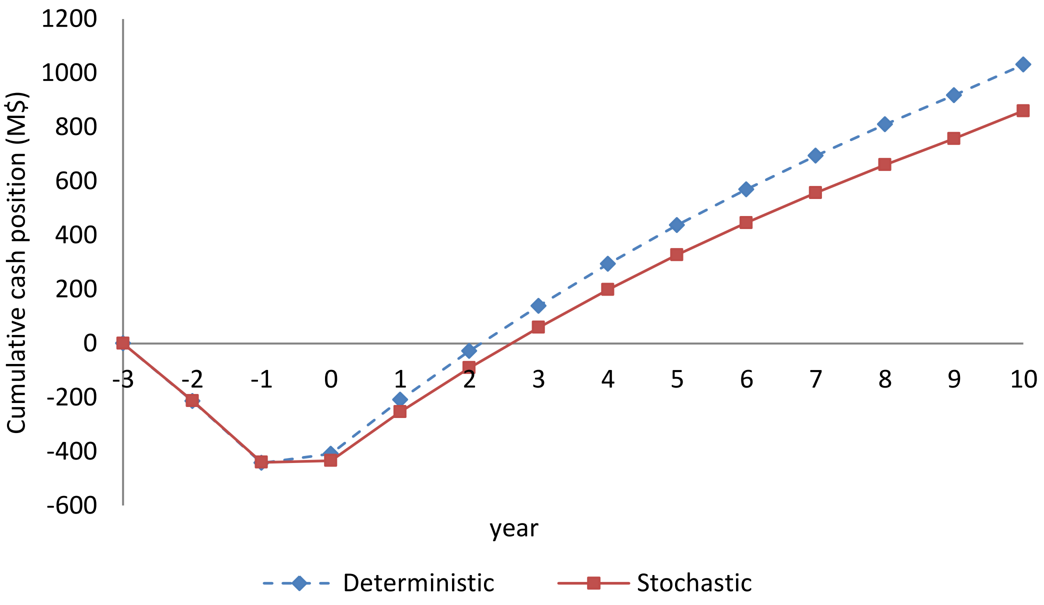

Figure 5 - Cumulative cash position for the deterministic and stochastic case studies.

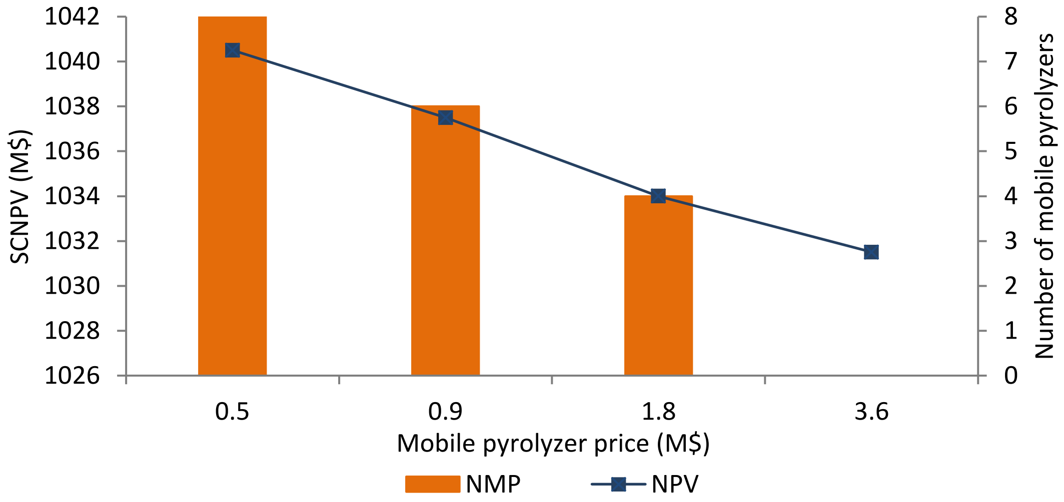

Figure 6 - Number of mobile pyrolyzers (NMP) in the supply chain and net present value (NPV) as function of the mobile pyrolysis price under deterministic conditions.

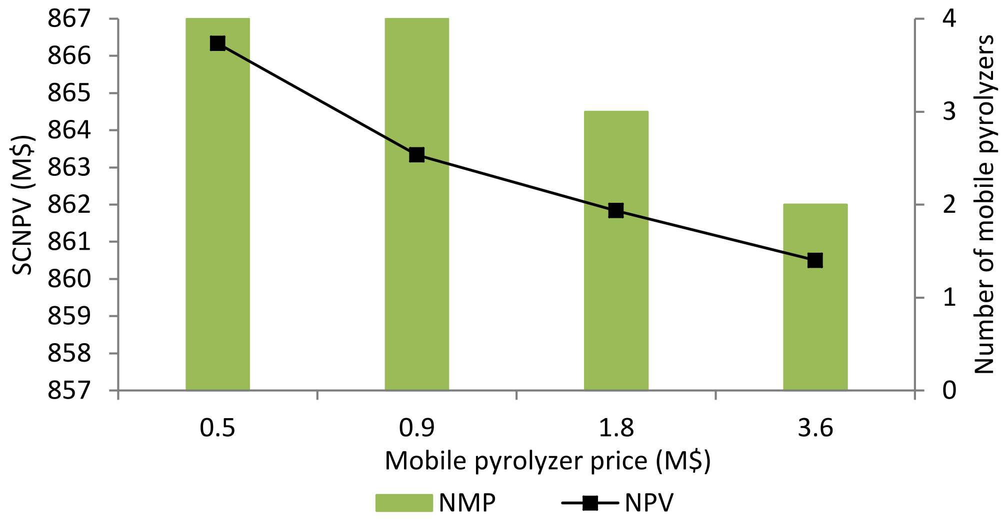

Figure 7 - Number of mobile pyrolyzers (NMP) in the supply chain and net present value (NPV) as function of the mobile pyrolysis price under stochastic conditions.

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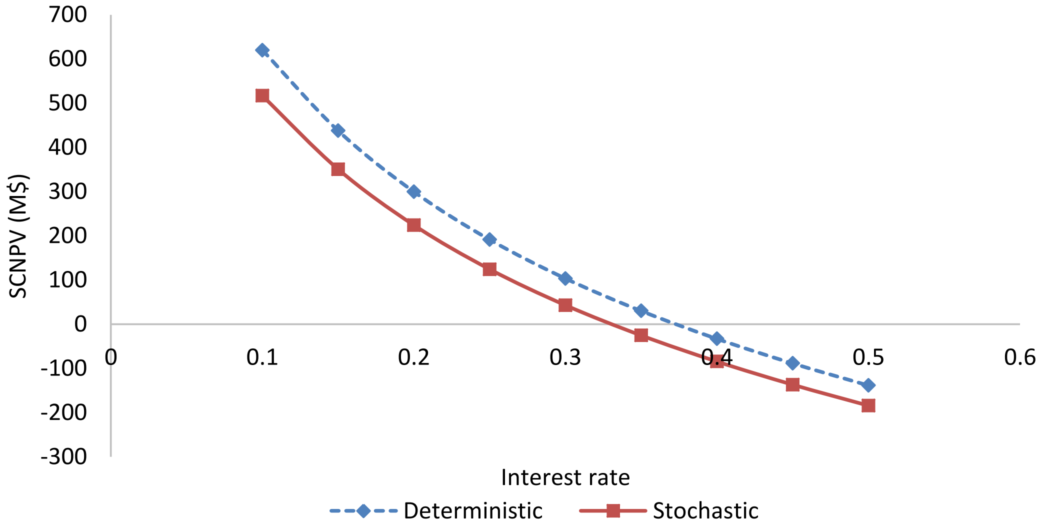

Figure 8 - Sensitivity of the supply chain net present value to the interest rate for the stochastic and deterministic cases.

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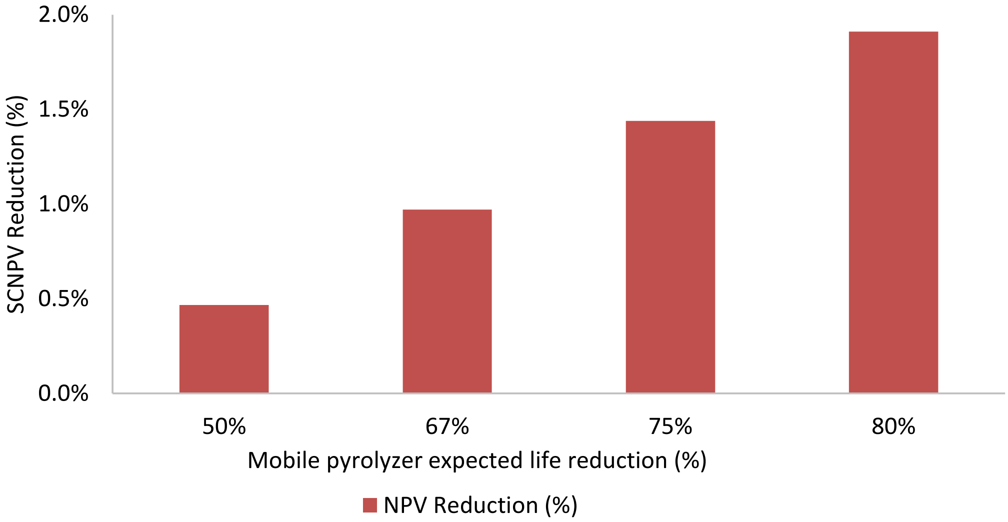

Figure 9 - Sensitivity of the supply chain net present value to the mobile pyrolysis unit depreciable life for the stochastic case.

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Table 1 - Conversion factors of the reactions.

Description	Conversion factor	Units	Reference
Pyrolysis oil on dry biomass for stationary plant	0.768	kg kg^{-1}	[6]
Gasoline and diesel on pyrolysis oil	0.528	dm^3 kg^{-1}	[6]
Pyrolysis oil on dry biomass for mobile pyrolyzer	0.583	kg kg^{-1}	[47]

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Table 2 - Total capital investment (TCI) is a function of purchased equipment costs.

Direct Costs	Solid-Fluid processing plant [45]
Purchased equipment installation	39% of purchasing cost
Instrumentation & Controls (installed)	26% of purchasing cost
Piping (installed)	31% of purchasing cost
Electrical systems (installed)	10% of purchasing cost
Buildings (including services)	29% of purchasing cost
Yard improvements	12% of purchasing cost
Total direct costs	**202% of purchasing cost**
Indirect Costs	
Engineering and supervision	32% of purchasing cost
Construction expenses	34% of purchasing cost
Legal expenses	4% of purchasing cost
Contractor's fee	19% of purchasing cost
Contingency	37% of purchasing cost
Total indirect costs	**126% of purchasing cost**
Fixed capital investment (FCI)	328% of purchasing cost
Working capital (WC)	5% of total capital investment
Total capital investment (TCI)	**WC+FCI**

Table 3 - Percentage of the fixed capital investment to pay during the plant construction and start-up.

Year	Percentage to be paid
-2	38%
-1	46%
0	16%

Table 4 - Total productions costs expressed as function of the operating labour or the fixed capital investment.

Item	Factor and basis
Operating supervision	95% of operating labour
Maintenance and repairs	2% of FCI
Taxes on property	1% of FCI
Insurance	1% of FCI

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Table 5 - The costs of feedstock.

Material	Cost	Reference
Hardwood biomass	83.33 \$ Mg^{-1} of dry biomass	[6]
Catalysts	38.62 \$ m^{-3} of product	[6]
Natural gas	85.19 \$ m^{-3} of product	[6]
Waste disposal	18.00 \$ Mg^{-1} of dry biomass	[6]

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Table 6 - Production yields and selling prices for the mobile pyrolyzer products.

Product	Production yield (Mass % of dry biomass)	Selling price
Pyrolysis oil	57	---
Biochar	27	40.80 ($ Mg^{-1} of dry biomass)
Syngas	15	---
Tar	1	---

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Table 7 - Fuel consumption parameters for different materials to transport.

Material	**Density**	**Unit**	**Reference**
Pyrolysis oil	1170	(kg m^{-3})	[54]
Chipped biomass	220	(kg m^{-3})	[55]
Gasoline/Diesel	660	(kg m^{-3})	[54]
Type of truck	**Volume**		
Freight truck	40	(m^3)	-
Tank lorry	40	(m^3)	-
Material	**Cost**	**Units**	
Chipped biomass (50% moisture)	103.3	\$ km^{-1} Gg^{-1}	Calculated
Pyrolysis oil	19.3	\$ km^{-1} Gg^{-1}	Calculated
Gasoline and Diesel	27.3	\$ km^{-1} dam^{-3}	Calculated

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Table 8 - List of scenarios and behaviour of the uncertain variables.

Scenario	Biomass availability	Demand London	Demand Liverpool
1	High	High	High
2	High	High	Low
3	High	Low	High
4	High	Low	Low
5	Low	High	High
6	Low	High	Low
7	Low	Low	High
8	Low	Low	Low

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Table 9 - Optimal throughput of fast pyrolysis and pyrolysis oil upgrading plants [deterministic case]

Processing location	Fast pyrolysis section (Gg y^{-1} of biomass)	Pyrolysis oil upgrading section (Gg y^{-1} of pyrolysis oil)
Bristol	368	305
Liverpool	297	244

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Table 10 - Optimal flow rate of biomass between suppliers and fast pyrolysis centres [deterministic case]

Fast Pyrolysis	Bristol		Liverpool		
Supplier	**Hereford**	**Exeter**	**Longridge**	**Hull**	**Luton**
Biomass flow rate in Gg y^{-1} (% of available raw material used)	175 (100%)	193 (42%)	210 (100%)	50 (100%)	37 (34%)

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Table 11 –Optimal flow rate of gasoline and diesel between suppliers and fast pyrolysis centres [deterministic case]

Consumption area	**London**		**Liverpool**
Pyrolysis oil Upgrading	**Bristol**	**Liverpool**	**Liverpool**
Biofuel flow rate in dam^3 y^{-1} (% of demand supplied)	161 (80%)	40 (20%)	89 (100%)

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Table 12 - Optimal throughput of fast pyrolysis and pyrolysis oil upgrading plants [stochastic case]

Processing location	Fast pyrolysis section (Gg y^{-1} of biomass)	Pyrolysis oil upgrading section (Gg y^{-1} of pyrolysis oil)
Bristol	357	313
Liverpool	288	237

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Table 13 - Optimal flow rate of biomass between suppliers and fast pyrolysis centres [stochastic case]

	Fast Pyrolysis	Bristol			Liverpool		
	Supplier type 1	**Hereford**	**Exeter**	**Longridge**	**Hull**	**Hereford**	**Luton**
Biomass flow rate in Gg y^{-1} (% of available raw material used)	Sc1	148 (85%)	209 (46%)	210 (100%)	50 (100%)	27 (15%)	-
	Sc2	175 (100%)	181 (40%)	210 (100%)	43 (86%)	-	-
	Sc3	175 (100%)	181 (40%)	210 (100%)	-	-	-
	Sc4	175 (100%)	148 (33%)	210 (100%)	-	-	-
	Sc5	146 (100%)	211 (56%)	175 (100%)	42 (100%)	-	71 (77%)
	Sc6	146 (100%)	211 (56%)	175 (100%)	42 (100%)	-	37 (40%)
	Sc7	146 (100%)	211 (56%)	175 (100%)	36 (86%)	-	-
	Sc8	146 (100%)	211 (56%)	175 (100%)	1 (2%)	-	-

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Table 14 - Optimal flow rate of biomass used in the mobile pyrolyzers, and the upgrading plants where the pyrolysis oil was sent to [stochastic case]

	Pyrolysis oil Upgrading	Bristol			Liverpool
	Supplier type 2	Dulverton	Machynlleth	Builth Wells	Kendal
Biomass flow rate in Gg y^{-1} (% of available raw material used)	Sc1	12 (100%)	7 (58%)	12 (100%)	-
	Sc2	12 (100%)	3 (25%)	12 (100%)	4 (33%)
	Sc3	12 (100%)	7 (58%)	12 (100%)	-
	Sc4	12 (100%)	3 (25%)	12 (100%)	4 (33%)
	Sc5	12 (100%)	7 (58%)	12 (100%)	-
	Sc6	12 (100%)	3 (25%)	12 (100%)	4 (33%)
	Sc7	12 (100%)	7 (58%)	12 (100%)	-
	Sc8	12 (100%)	3 (25%)	12 (100%)	4 (33%)

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Table 15 - Optimal flow rate of gasoline and diesel between suppliers and fast pyrolysis centres [stochastic case]

	Consumer	London		Liverpool
	Pyrolysis oil Upgrading	Bristol	Liverpool	Liverpool
Biofuel flow rate in $dam^3 y^{-1}$ (% of demand supplied)	Sc1	165 (82%)	36 (18%)	89 (100%)
	Sc2	164 (82%)	37 (18%)	75 (100%)
	Sc3	164 (98%)	3 (2%)	89 (100%)
	Sc4	150 (90%)	17 (10%)	75 (100%)
	Sc5	165 (82%)	36 (18%)	89 (100%)
	Sc6	164 (82%)	37 (18%)	75 (100%)
	Sc7	164 (98%)	3 (2%)	89 (100%)
	Sc8	163 (98%)	4 (2%)	75 (100%)