MULTIOBJECTIVE OPTIMIZATION OF BIOMASS-TO-LIQUIDS PROCESSING NETWORKS

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Abstract

This paper addresses the optimal design and planning of biomass-to-liquids (BTL) supply chains under economic and environmental criteria. The supply chain consists of multisite distributed-centralized BTL processing networks. The economic objective is measured by the total annualized cost, and the measure of environmental performance is the life cycle greenhouse gas emissions. A bi-criterion, multi-period, mixed-integer linear programming model is proposed that takes into account diverse conversion pathways and technologies, feedstock seasonality, geographical diversity, biomass degradation, infrastructure compatibility, and government incentives. The model simultaneously predicts the optimal network design, facility location, technology selection, capital investment, production planning, inventory control, and logistics management decisions. The problem is solved with the ε-constraint method, and the resulting Pareto curve reveals how the optimal annualized cost and the BTL processing network structure change under different specifications of environmental performance. The proposed approach is illustrated through a county-level case study for the state of Iowa.

Keywords

Design, planning, biofuels supply chains, multiobjective optimization, life cycle analysis

Introduction

Biomass-to-liquids (BTL) technologies, which convert cellulosic biomass to liquid hydrocarbon fuels, are a promising approach for future biofuel production. The main reason is that compared with ethanol fuel, biomass-derived gasoline and diesel fuels can be used directly in today’s gasoline- and diesel-powered vehicles, and are compatible with the current gasoline/diesel distribution infrastructure and could be transported directly through existing gasoline/diesel pipelines, dispensed at existing fueling stations, and sold at any existing retail station pumps. Existing BTL technologies either are based on gasification followed by Fischer-Tropsch (FT) conversion or are based on pyrolysis followed by hydroprocessing. A number of pre-conversion technologies have also been developed that convert biomass into intermediates, such as bio-oil or bio-slurry, before upgrading to liquid fuels. This method leads to a BTL distributed-centralized processing networks, in which a number of distributed pre-conversion processes are built to reduce the feedstock transportation costs and a centralized intermediate upgrading plant is built to take advantage of the economy of scale. However, this type of network introduces more tradeoffs among capital, operating, transportation and storage costs, which lead to a significant challenge to determine the most economic network design. Moreover, in observance of the Renewable Fuel Standards, the BTL supply chain must not only be economically viable but also be environmentally sustainable. Thus, it is important

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to optimize the design and operations decision of BTL supply chain from both strategic and operational levels and to assess and improve the economic and environmental performance of biomass-derived liquid fuels from a life cycle perspective.

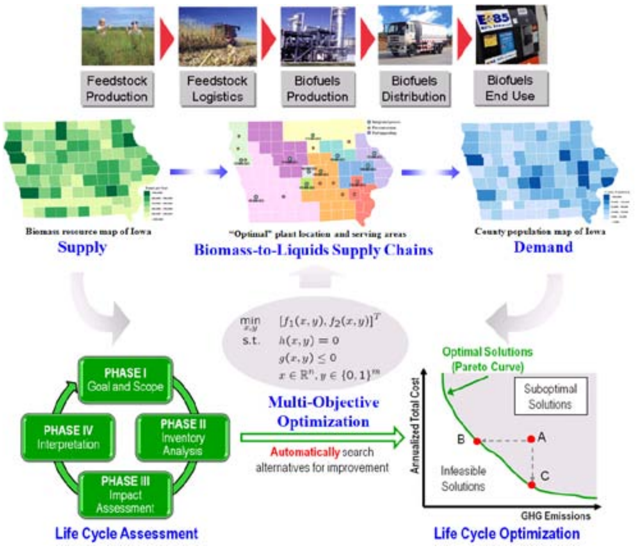

Figure 1. Life cycle optimization of biomass-to-liquids supply chains in Iowa

In this work, we address the optimal design and planning of BTL supply chains under economic and environmental criteria. The supply chain consists of multisite distributed-centralized processing networks for BTL conversion. A multiperiod mixed-integer linear programming (MILP) model is proposed that takes into account the main characteristics of BTL supply chains, such as seasonality of feedstock supply, biomass deterioration with time, geographical diversity, availability of biomass resources, moisture content, diverse conversion pathways and technologies, infrastructure compatibility, demand distribution, and government subsidies. The MILP model integrates decision-making across multiple temporal and spatial scales and simultaneously predicts the optimal network design, facility location, technology selection, capital investment, production operations, inventory control, and logistics management decisions. In addition to the economic objective of minimizing the total annualized cost, the MILP model is integrated with life cycle analysis (LCA) through a multiobjective optimization scheme to include another objective of environmental performance measured by life-cycle greenhouse gas emissions. The multiobjective optimization framework allows the model to establish tradeoffs between the economic and environmental performances of the BTL supply chains in a systematic way. The multiobjective optimization problem is solved with the ε-constraint method and produces Pareto-optimal curves that reveal how the optimal annualized cost, biomass processing, and fuel production network structures change with different environmental performance of the BTL supply chain. The proposed optimization approach is illustrated through a case study based on the BTL supply chain for the state of Iowa. The scope of this work is given in Fig. 1.

In the rest sections, we first introduce the problem statement, and then present the results of the county-level case study in Iowa. Conclusions are given at the end.

Problem Statement

In this problem, we are given a set of biomass feedstocks and their major properties (e.g., moisture content, degradation rate, harvesting windows, etc.). The biomass feedstocks can be converted to a set of liquid hydrocarbon fuels through a number of conversion technologies. These technologies include, but are not limited to, gasification followed by Fischer–Tropsch synthesis and fast pyrolysis followed by hydroprocessing. Biomass feedstocks can also be first converted into intermediate products (e.g. bio-oil and bio-slurry) through rotating cone reactor pyrolysis and fluidized bed reactor pyrolysis, before upgrading the intermediates to liquid fuel with corresponding technologies.

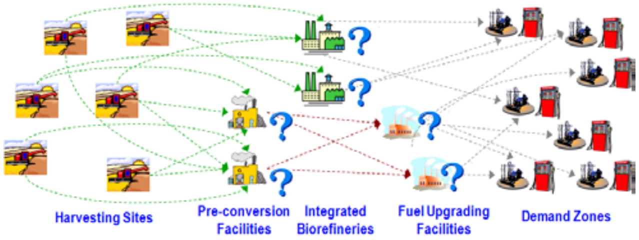

Figure 2. Biomass-to-liquids supply chain superstructure.

A planning horizon of one year is divided into several time periods. The duration of each time period is known, and the project lifetime in terms of years is given. We assume a constant discounted rate throughout the project lifetime. The government incentives, including production and construction incentives, are given. We are also given a BTL supply chain network superstructure (see Figure 2), including a set of harvesting sites and a set of demand zones, as well as the potential locations of integrated biorefineries, preconversion facilities, and intermediate upgrading facilities. We are given the availability of each type of biomass feedstock in each harvesting site and the upper and lower bounds of the demands of liquid fuels in each demand zone at each time period. A set of capacity levels is given for all the production facilities and the costs of different technologies at different capacity levels are known. Intermediate and fuel yields and operating costs are also given. The unit cost and environmental burden associated with feedstock acquisition, liquid fuel distribution in local regions, biomass processing, and fuel production are known. The network also includes different types of transportation links as shown in Fig. 2. For each transportation link, the transportation capacity, available transportation modes, unit transportation cost of each mode, transportation distance, and emissions of each transportation type are known.

The objectives are simultaneous minimizing the annualized total cost (which is the measure of the economic performance) and the life cycle field-to-wheel greenhouse gas (GHG) emissions (which measures the environmental performance) of the entire BTL supply chain through optimizing the following decision variables:

- Number, sizes, locations, and technology selections of each processing facilities
- Feedstock harvesting schedule at each harvest site
- Inventory levels of feedstocks, intermediates, and liquid fuels at each facility in each time period
- Fuel yield and feedstock consumption rates at each facility in each time period
- Transportation profiles of each transportation link and transportation mode

Model Formulation

We develop a bicriterion, multiperiod MILP model for the problem addressed in this work. In this section, we present the structure of the model and how it takes into account the various characteristics of BTL supply chains. Due to the length limit of this paper, we will not present the detailed mathematical model. Interested readers please refer to You and Grossmann (2011) for details.

The model includes five major types of constraints for the BTL processing network. The first type of constraints is for the biomass feedstock supply system that accounts for the following issues:

- Seasonal supply and availability of biomass sources
- Mass balance at each harvest site
- Weight capacities of transportation links from harvest sites to integrated biorefineries and preconversion facilities, after considering moisture content and adjusting the standardized weights of different biomass resources

The second to the fourth types of constraints are for the integrated biomass-to-liquid conversion facilities, biomass preconversion facilities, and intermediate upgrading facilities, respectively. Each type of constraints considers the following issues:

- Mass balance of input materials (e.g. biomass or intermediate bio-oils) at each facility
- Mass balance of output materials (e.g. biofuels or intermediate bio-oils) at each facility
- Selection of conversion technologies
- Selection of capacity levels
- Production capacity definition
- Investment cost as a function of the capacity
- Fixed annual O&M cost as a function of capacity
- Limits of incentives provided by the government
- Input-output mass balance of each facility
- Production level constraints
- Minimum inventory (or safety stock) level of each facility

The last type of constraints is for the liquid transportation fuel distribution system, where we take into account the time-dependent demand of each fuel at each time period and the corresponding demand upper and lower bounds.

We consider two objectives in this model. The economic objective is to minimize the annualized total cost, including the total annualized capital cost, the annual operation cost, and the annual governmental incentive. The total capital cost includes the total investment costs of integrated biorefineries, preconversion facilities, and intermediate upgrading facilities. The annual operational cost includes biomass feedstock acquisition cost, the local distribution cost of final fuel product, the production costs of intermediate and final products, and the transportation and storage costs of biomass feedstocks, intermediates, and final products. In the production cost, we consider both the fixed annual operating cost, which is given as a percentage of the corresponding total capital investment, and the net variable cost, which is proportional to the processing amount. We note the credit from byproduct (e.g., charcoal) is taken into account in the "net" variable production cost. In the transportation cost, both distance-fixed cost and distance-variable cost are considered. The government incentive includes construction incentive and volumetric incentive for biofuel production and usage. The construction incentive should be converted into annualized incentive after considering discount rate and project lifetime. The volumetric incentive for biofuel production and usage is proportional to the quantity of biomass-derived liquid transportation fuel sold to the demand zones. Thus, the annual government incentive is

The environmental objective is to minimize the total annual CO2-equivalent greenhouse gas (GHG) emission resulting from the operations of the BTL supply chains. The formulation of this objective is based on the field-to-wheel life cycle analysis, which takes into account the following life cycle stages of biomass-based liquid transportation fuels:

- Biomass cultivation, growth, and acquisition
- Soil carbon sequestration of biomass feedstocks (emission credit)
- Biomass transportation of from source locations to processing facilities
- Biomass storage at integrated biorefineries and preconversion processes

- Emissions from integrated biorefineries and preconversion facilities
- Transportation of intermediate products from preconversion facilities to intermediate upgrading facilities
- Storage of intermediate products in intermediate upgrading facilities
- Emissions from intermediate upgrading facilities
- Transportation of liquid transportation fuels from integrated biorefineries and intermediate upgrading facilities to the demand zones
- Local distribution of liquid transportation fuels in demand zones
- Emissions from biofuels usage in vehicle operations

We note that carbon uptake resulting from biomass growth offsets the emissions from vehicle operation using biofuels and the emissions from biomass processing (Laser et al. 2009). However, the emissions from production processes should include those from utility generation and byproduct (e.g., char) utilization. In addition, carbon sinks (such as soil carbon sequestration) should be taken into account as part of the emission credit in the life cycle analysis (Farrell et al., 2006). Therefore, the environmental objective accounts for the emissions from biomass acquisition, liquid transportation fuel distribution, biomass conversion and liquid fuel production, feedstock, intermediate and fuel product transportation, and biomass and intermediate storage, as well as emission credits from soil carbon sequestration.

County-Level Case Study for the State of Iowa

We used the optimization framework described in You and Wang (2011) to solve a county-level case study for the state of Iowa. All the computational studies were performed on a workstation with Intel Core2 Quad 2.40 GHz CPU and 3.24 GB RAM. The MILP model was coded in GAMS 23.6.357 and solved with the solver CPLEX 12 with four processing cores under parallel mode. The optimality tolerances were all set to 0.01%

The state of Iowa comprises 99 counties. In this case study, each county in Iowa is considered as a harvesting site, a potential location of an integrated biorefinery facility, a possible preconversion facility location, a possible site of intermediate upgrading facility, and a demand zone. To investigate the impacts of feedstock supply seasonality, twelve time periods are consider for each year (i.e., one month as a time period). Three major types of biomass resources are considered: crop residues (e.g., corn stover), energy crops (e.g., switchgrass and miscanthus), and wood residues (e.g., forest residues and primary mills, secondary mills, urban wood residues). Two types of liquid fuels products, gasoline and diesel, are considered, and their monthly demands in each county were obtained from Energy Information Administration based on the year 2010 data. We consider two integrated conversion method (gasification + FT synthesis and pyrolysis + hydro-processing), two pre-conversion technologies (rotating cone reactor pyrolysis and fluidized bed reactor pyrolysis), and two types of intermediate upgrading facilities (bio-oil to FT liquids and bio-slurry to FT liquids). Each conversion facility has three capacity levels. Three major transportation modes (rail, trucks, and pipelines) are considered for all transportation links.

To simultaneously optimize the economic and environmental performances of the BTL supply chains, we solve the multiobjective optimization problem with the ε–constraint method. The resulting bi-criterion MILP problem includes 1,782 binary variables, 4,294,326 continuous variables, and 772,506 constraints. The entire solution process takes a total of 3,815,104 CPU-seconds (around 1,060 CPU-hours) for all 22 instances. The resulting Pareto curve is given in Figure 3.

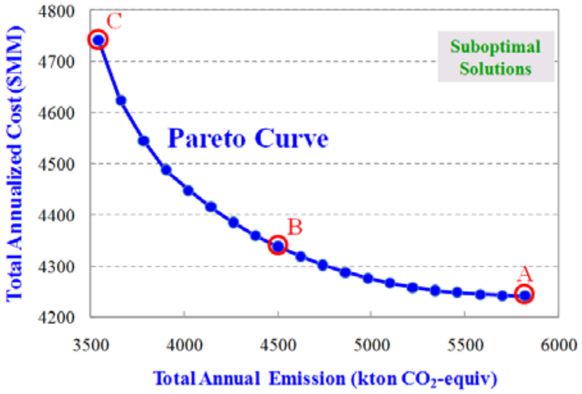

Figure 3. Pareto curve showing trade-off between economic vs. environmental performances of the BTL supply chain

We can see from Figure 3 that as the optimal total annualized cost reduces from around $4,732MM to around $4,233MM, the annual GHG emissions resulting from the operation of the BTL supply chain increases from around 3,543 Kton CO_2-equiv to around 5,821 Kton CO_2-equiv. The trend of this Pareto curve shows that the lower the total annualized cost is, the more GHG emissions are resulted from the operation of the BTL supply chain. In particular, the unit supply chain costs of biomass-derived liquid fuels in points A, B and C are $3.60/GEG, $3.68/GEG and $4.02/GEG, respectively, while their corresponding total annual GHG emissions are 5,821 Kton/CO2-eq, 4,502 Kton/CO2-eq, and 3,543 Kton/CO2-eq, respectively. We can see that from point A to point B, the annual GHG emissions have been significantly reduced, while there is only small increase of the total unit fuel cost. It implies that the design of point B might be a "good choice" solution. We note that the annualized cost has taken into account government incentives, which include biorefinery construction incentives and volumetric incentives for fuel production (e.g. $1.01/gallon for cellulosic biofuels and $1.00/gallon for biodiesel).

The optimal number, size, location and technology selection of the all conversion processes for these three solutions are given in Figure 4.

Figure 4(A), which has the population density map as the background, is for the optimal BTL supply chain design for the minimum cost solution, corresponding to point A in Figure 3. We can see that in this case six integrated conversion facilities are built, with capacities ranges from 100 MM GEG/year to 182 MM GEG/year. All the integrated conversion facilities in this case select the conversion technology of fast pyrolysis followed by hydroprocessing, because this technology has a relatively higher yield of gasoline, the demand for which is larger than for diesel in Iowa. We can also see from this figure that 12 preconversion facilities and 3 fuel upgrading facilities are selected to be built. All the preconversion facilities utilize fluidized bed reactor pyrolysis, with capacities ranges from 540 Kton/year to 1712 Kton/year. Consequently, all the fuel upgrading facilities convert bio-slurry into FT liquids, with capacities rangeing from 110 MM GEG/year to 228 MM GEG/year. We note that all the integrated conversion facilities and fuel upgrading facilities are located in counties with relatively large population and that the preconversion facilities are usually in counties near the ones for fuel upgrading facilities. Such location decisions certainly lead to lower average transportation distance of intermediates and liquid transportation fuels.

In Figure 4(B), we show the optimal BTL supply chain design of the "good choice" solution (as point B in Figure 3) with a map of total biomass resources distribution in Iowa as the background. We observe that all the plant location and technology selection decisions are the same as the minimum cost solution, although the optimal sizes of the plant change. We can also see that preconversion facilities and integrated conversion facilities are located in counties with abundant biomass resources. As a result, both emission of biomass resources (which has relatively low density) and transportation cost can be reduced.

Figure 4(C) shows the optimal locations of the conversion processes, each plant's capacity and conversion technology, and the counties primarily supplied by the integrated conversion facilities or fuel upgrading facilities for the minimum emission solution (point C of Figure 4). We can see that there are 7 integrated conversion facilities, all using the technology of fast pyrolysis followed by hydroprocessing, with capacities ranging from 115 MM GEG to 198 MM GEG. In addition, 10 preconversion processes are built to produce bio-slurry, which are shipped to 4 fuel upgrading facilities with capacities ranging from 89 MM GEG to 156 MM GEG for the production of liquid fuels. More conversion facilities are selected to install in this case than in the previous two cases. Although the capital cost increases as the number of plants increases, because of economy of scale, the average transportation distance for feedstock and fuel products is significantly reduced. Moreover, the shorter average transportation distance also leads to a reduction of total GHG emissions, since road transportation is the major mode for shipping feedstocks and intermediates. Figure 14 also shows the service area of each fuel production facility (integrated conversion facilities or fuel upgrading facilities). We note that if a county is supplied by more than one fuel production facilities, we consider this county to be served by its major supplier in terms of GEG. Similarly, the service areas of fuel production processes reveal the tradeoffs among capital, production, storage, and transportation cost.

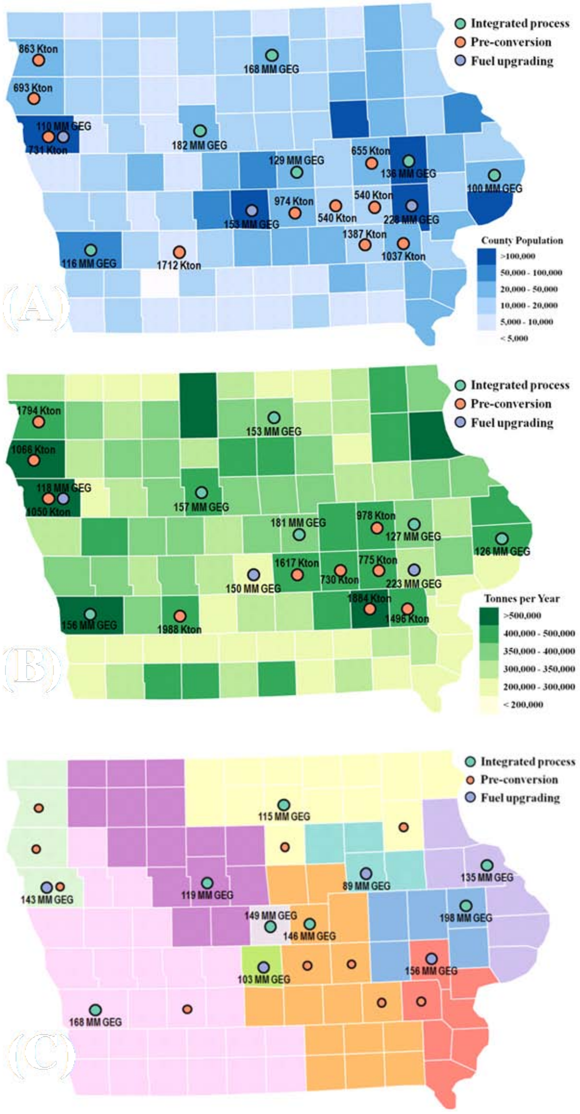

Figure 4. Optimal plant types, locations, and capacities of the BTL supply chain for the minimum cost solution (point A), the "best

choice" solution (point B), and the minimum emission solution (point C). Background of (A) is the map of population distribution, of (B) is the map for biomass resources, and of (C) is a map for the serving areas of integrated conversion and fuel upgrading facilities.

The optimal designs of the three solutions have similarities. For instance, preconversion facilities and integrated conversion facilities are usually located in the counties with abundant cellulosic biomass resources, whereas fuel production processes are usually closer to the counties with large population. Such facility location decisions are mainly due to the lower transportation density of cellulosic biomass resources and their high unit transportation costs and emissions.

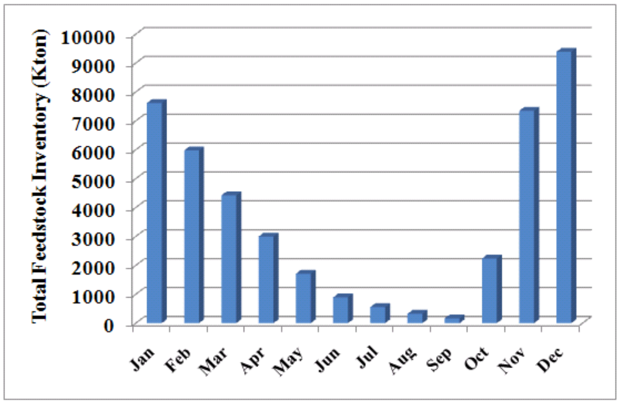

Figure 5. Total inventory of feedstocks in each month for the solution in point B.

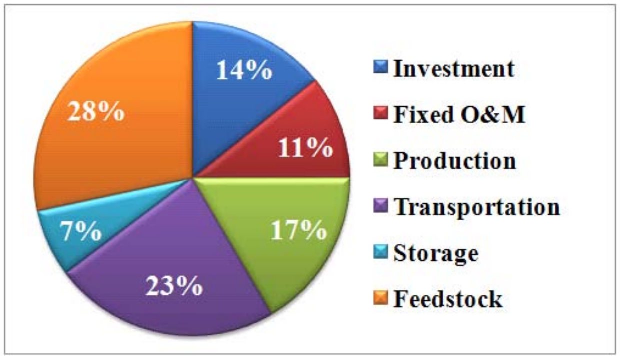

Figure 6. Cost breakdown for the solution in point B.

Fig. 5 shows the total inventory level for all the feedstock biomass sources in each month for the "good choice" solution (Point B). As corn stovers contribute a significant amount of the total biomass resources in Iowa, we can see there is a strong seasonality in the inventory profile. The total inventory level first increases from the minimum around 100 Kton in September to the maximum of around 9,000 Kton in December, and then decreases to the minimum in September next year. This trend is due to the harvesting season of corn stovers, which is a byproduct of corn harvesting from October to November every year. Because of the capacity limit, however, not all the feedstocks harvested from October to November can be converted to liquid transportation fuels or intermediate. Another reason is that each fuel production plant, once it is installed, should maintain a minimum production level. Thus, a significant proportion of the agricultural residues are stored in order to keep down the installation sizes of the plants and avoid supply/production disruption.

Figure 16 shows the breakdown of the total cost for the "good choice" solution (Point B in Figure 11). We can see the total capital investment (after considering incentives), fixed O&M and variable production cost contribute around 14%, 11%, and 17% of the total cost, respectively. Feedstock acquisition cost and transportation cost both contribute around a quarter of the total cost, while the cost for storage consists of only 7%. The results shown in Figure 16 suggest that conversion efficiency and equipment utilization, contributing to 42% of the total cost, are the bottlenecks to reducing the biomass-derived liquid transportation fuel cost. It is therefore of great importance to develop advanced conversion processes to reduce both capital and variable production costs.

Conclusion

In this paper, we describe an MILP approach for the design and planning of BTL supply chains under economic and environmental criteria. The proposed optimization approach is illustrated through a case study for the county-level BTL supply chain for the state of Iowa. The results show that improving the conversion technologies is the key issue in overcoming the barrier of commercializing biomass-derived liquid fuels.

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