**Supporting Information**

**Sustainable Product Design: A Life-Cycle Approach**

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# Revised Fabric Geometry Model for Calculating Young’s Modulus and Shear Modulus of Composite Bumper Beam

The revised Fabric Geometry Model (*rFGM*) was proposed to represent the material-structure-property relationship for fiber-matrix composite materials. By using this model, the Young’s modulus and shear modulus of composite bumper beam can be calculated based on the properties of fiber and matrix, their volume fractions, and the fibers’ spatial orientations.1-3 As elaborated below, the model consists of four components:

1. Calculation of fiber and matrix properties
2. Calculation of local stiffness matrix for single composite rod
3. Identification of fibers’ spatial orientation
4. Transformation from local stiffness matrix to global stiffness matrix

## Calculation of Fiber and Matrix Properties

As shown in Eq. S1-2, the properties of fiber and matrix are controlled by the binary variables and , respectively. If the -th fiber candidate (or the -th matrix candidate) is selected, (or ) is equal to 1. Otherwise, it is equal to 0.

(S1)

(S2)

The subscripts and denote the fiber and matrix, respectively. , , , , and are the Young’s modulus, shear modulus, Poisson’s ratio, density, and heating value, respectively. The properties of the fiber candidates and matrix candidates are listed in Table 6.

## Calculation of Local Stiffness Matrix for a Single Composite Rod

In the , it is assumed that composite material is made of a set of transversely isotropic composite rods having various spatial orientations. Each composite rod consists of unidirectional reinforcing fibers and polymeric matrix. The volume fraction of the composite rod in each spatial orientation varies while the mechanical properties of the composite rod with respect to the local coordinate are the same. For a single composite rod, its mechanical properties in the local coordinate (i.e., local stiffness matrix, Young’s modulus, shear modulus) depend on the properties of fibers and matrix as well as their volume fractions.

Consider the *r*-th composite rod. Since the composite rod is assumed to be transversely orthotropic, the local stiffness matrix () can be expressed as

(S3)

where are the elements of the local stiffness matrix, which are calculated based on the mechanical properties in Eq. S4-16.2

(S4)

(S5)

(S6)

(S7)

(S8)

(S9)

(S10)

(S11)

(S12)

(S13)

(S14)

(S15)

(S16)

The subscript *x-y-z* stands for the local coordinate for the composite rod. , , and denotes the fiber direction, the transverse direction of the fiber, and the orthogonal to the and directions. The properties (, , , , , , and ) of the composite rod are determined by using the micro-mechanics models (Eq. S17-24) for the transversely isotropic composite rod.4,5 Eq. S17-18 which are known as the rule of mixtures calculate the Young’s modulus in the fiber direction () and the major Poisson’s ratio ().

(S17)

(S18)

where and are the volume fractions of the fiber and matrix in a composite rod, respectively. Clearly, their summation is equal to 1.

(S19)

Eq. S20-21 calculate the Young’s modulus in the transverse direction to the fiber () and the shear modulus in the *x-y* plane (), respectively.

(S20)

(S21)

The reciprocal relation (Eq. S22) is used to calculate the minor Poisson’s ratio .

(S22)

The Poisson’s ratio () and the shear modulus in the *y-z* plane () are decided by Eq. S23-24.

(S23)

(S24)

## Identification of Spatial Orientation for Composite Rod

The spatial orientation of the unidirectional composite rod is identified here. The global coordinate *X-Y-Z* is considered for the composite bumper beam. In general, the spatial orientation can be represented as a 3-D vector of unit magnitude, namely [, , ] and . Here, , , are the global coordinates of the *X*, *Y*, and *Z* directions. Then, the vector ([, , ]) representing the transverse direction of the composite rod is given by,

(S25)

(S26)

(S27)

The third vector ([, , ]) that is orthogonal to the two above vectors is calculated as

(S28)

(S29)

(S30)

## Transformation from Local Stiffness Matrix to Global Stiffness Matrix

Based on the spatial orientation of a composite rod, its local stiffness matrix is transformed to fit the global coordinate and generate the global stiffness matrix. With the three vectors above, the geometric strain transformation matrix of the *r*-th composite rod system can be represented as follows2

(S31)

This transformation matrix is used to transform the local stiffness matrix into the global stiffness matrix ().

(S32)

Afterwards, the global stiffness matrix of composite rods with different spatial orientations are superimposed with respect to their volume fractions to calculate the stiffness matrix () of the bumper beam.

(S33)

where is the volume fraction of the *r*-th composite rod. Finally, it is assumed that when stress is applied in certain direction, the bumper beam only deform in the same direction and the strain (deformation) in the other directions are negligible. Therefore, based on the generalized hooke’s law,4 the Young’s modulus ( and ) in the *X-X* and *Y-Y* directions and the shear modulus () in the X-Y plane are calculated as follows

(S34)

(S35)

(S36)

# Life Cycle Inventory Data for the Composite Bumper Beam Case Study

## Raw Material Production Stage

Table S4.1: Life Cycle Inventory (LCI) Data for the Production of Fibers and Matrix

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Input | | Output | | |
| Facilities | Ref.a | Product | 1 kg **carbon fiber** | |
| Materials | Byproducts | Ref.a | |
| Energy | Emissions |
| Manpowerb | 7.74×10-6 job |  |  | |
| Input | | Output | |
| Facilities | Ecoinvent 3.4 | Product | 1 kg **glass fiber** |
| Materials | Byproducts | Ecoinvent 3.4 |
| Energy | Emissions |
| Manpowerc | 5.53×10-6 job |  |  |
| Input | | Output | |
| Facilities | Ecoinvent 3.4 | Product | 1 kg **kenaf fiber** |
| Materials | Byproducts | Ecoinvent 3.4 |
| Energy | Emissions |
| Manpowerd | 1.35×10-6 job |  |  |
| Input | | Output | | |
| Facilities | Ecoinvent 3.4 | Product | 1 kg **jute fiber** | |
| Materials | Byproducts | Ecoinvent 3.4 | |
| Energy | Emissions |
| Manpowerd | 3.99×10-6 job |  |  | |
| Input | | Output | | |
| Facilities | Ecoinvent 3.4 | Product | 1 kg **polyester resin** | |
| Materials | Byproducts | Ecoinvent 3.4 | |
| Energy | Emissions |
| Manpowere | 6.4×10-7 job |  |  | |
| Input | | Output | | |
| Facilities | Ecoinvent 3.4 | Product | 1 kg **epoxy resin** | |
| Materials | Byproducts | Ecoinvent 3.4 | |
| Energy | Emissions |
| Manpowere | 6.4×10-7 job |  |  | |

|  |  |  |  |
| --- | --- | --- | --- |
| Input | | Output | |
| Facilities | Ecoinvent 3.4 | Product | 1 kg **polypropylene** |
| Materials | Byproducts | Ecoinvent 3.4 |
| Energy | Emissions |
| Manpowerf | 2.24×10-7 job |  |  |
| Input | | Output | |
| Facilities | Ecoinvent 3.4 | Product | 1 kg **polyethylene** |
| Materials | Byproducts | Ecoinvent 3.4 |
| Energy | Emissions |
| Manpowerg | 3×10-7 job |  |  |
| Input | | Output | |
| Facilities | Ecoinvent 3.4 | Product | 1 kg **polyethylene terephthalate** |
| Materials | Byproducts | Ecoinvent 3.4 |
| Energy | Emissions |
| Manpowerh | 1.9×10-6 job |  |  |

1. <http://ecocostsvalue.com/EVR/model/theory/subject/5-data.html>
2. <https://www.knoxnews.com/story/money/business/2016/10/12/lemond-composites-marks-opening-oak-ridge/91969622/>
3. <https://iacmi.org/2016/03/30/kentucky-glass-fiber-manufacturer-announces-expansion-32-new-jobs-created/>
4. <https://www.cdc.org.nz/wp-content/uploads/2014/12/aeru-value-of-irrigation-report.pdf>
5. assumed
6. <https://www.bizjournals.com/houston/news/2017/06/22/brazil-petrochem-co-to-build-675m-project-in.html>
7. <https://www.lyondellbasell.com/en/la-porte-complex/news/lyondellbasell-begins-construction-of-hyperzone-pe-plant-at-its-la-porte-complex/>
8. <http://www.chemicals-technology.com/projects/-mg-pet-plant-corpus-christi-texas>

## Transportation

It is assumed that the transportation distance among any two life cycle stages is set equal to 300 km. In addition, all materials and products are transported by using the 16-32 ton based lorry. The LCI data for transporting 1 ton material by 1 km is listed as follows:

Table S4.2: LCI Data for Transportation

|  |  |  |  |
| --- | --- | --- | --- |
| Input | | Output | |
| Facilities | Ecoinvent 3.4 | Product | 1 **ton-kilometer transportation** |
| Materials | Byproducts | Ecoinvent 3.4 |
| Energy | Emissions |
| Manpowera | 7.7×10-6 job |  |  |

1. Assumed (two drives, 2080 driving hours per year; one-way transportation takes one hour to delivers 15 ton goods for 100 km)

## Product Manufacturing

In the product manufacturing stage, there are two processes. The first process is the manufacturing of composite bumper beam by using the injection molding. Table S3 lists the LCI data for the injection molding process. The data of input fibers and polymer matrix is decided by product design. The data of input facilities and labors as well as the output of byproducts and emissions are obtained from the Ecoinvent database. Moreover, the amount of input energy presumably depends on the selection of polymeric matrix since most of the energy (more than 70%) is used to melt and cool the matrix.6 The second process is the assembly of the bumper beam to the automotive vehicle. It is estimated that 0.5 kWh/kg bumper beam electricity is consumed to assemble an automotive component.

Table S4.3: LCI Data for the Inject Molding Process at Product Manufacturing Stage

|  |  |  |  |
| --- | --- | --- | --- |
| Input | | Output | |
| Facilities | Ecoinvent 3.4 | Product | **1 kg composites** |
| Materials | Decided by product design | Byproducts | Ecoinvent 3.4 |
| Energy | 2.96 kWh electricity (PR)a | Emissions |
|  | 4.46 kWh electricity (ER)b |  |  |
|  | 2.6 kWh electricity +  12.9 MJ natural gas (PP)c |  |  |
|  | 1.57 kWh electricity (PE)d |  |  |
|  | 1.51 kWh electricity (PET)c |  |  |
| Manpowere | 1.38×10-7 job |  |  |

1. Sujit D. Life cycle assessment of carbon fiber-reinforced polymer composites. *The International Journal of Life Cycle Assessment*. 2011; 16:268-282.
2. Deborah A.S., William R.M., Joseph W.C., Heather P. H. L. The manufacturing energy intensity of carbon fiber reinforced polymer composites and its effect on life cycle energy use for vehicle door light weighting. In: *Proceedings of the 20th International Conference on Composite Materials (ICCM)*. Copenhagen, Denmark. 2015.
3. Ana E, Javierre C, Elduque D, Fernández Á. LCI databases sensitivity analysis of the environmental impact of the injection molding process. *Sustainability*. 2015; 7: 3792-3800.
4. Ana E, Elduque D, Javierre C, Fernández Á, Jorge S. Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts. *Journal of Cleaner Production*. 2015; 108: 80-89.
5. Assumed that

## Product Use

Table S4 lists the LCI data for the use of composite bumper beam during the vehicle’s lifetime. The main impact is due to the consumption of fuels during the vehicle’s lifetime operation. The diesel is assumed to be the only fuel. The diesel () consumed by 1 kg bumper beam during the vehicle’s lifetime is calculated as follows:7

liter (S37)

where is lifetime driving distance (200, 000 km). is the weight of the vehicle curb (1650 kg). is the fuel-mass coefficient (0.6). is fuel consumption rate of the vehicle (0.056 L/km).

Table S4.4: LCI Data for Using Composite Bumper Beam During Vehicle’s Life Time

|  |  |  |  |
| --- | --- | --- | --- |
| Input | | Output | |
| Facilities | / | Product | 1 kg **bumper beam with**  **200,000 km driving distance** |
| Materials | / |
| Energy | 4.07 liter diesel | Byproducts | / |
| Manpower | / | Emissions | / |

## Product Recycling

### Pyrolysis process

Since there is no specific LCI data of the pyrolysis process in any database, pyrolysis process is modelled based on mass and energy balance equations and the obtained LCI data is listed in Table S5. The ‘chemical organic factory’ in the Ecoinvent database is presumably used as the input facilities. The input energy is used to pyrolyze polymers and the input energy is linearly proportional to the mass of polymeric matrix. Moreover, the product is the recovered fiber. and are the mass of the fiber and the composite bumper beam, respectively. The hydrocarbon liquids and gases obtained from the decomposition of matrix are combusted to generate electricity. Since their heating values are close to that of the matrix. Thus, the generated electricity () is calculated as

(S38)

where is the weight of matrix. is the heating value of the matrix.

Table S4.5: LCI Data for Pyrolysis Process

|  |  |  |  |
| --- | --- | --- | --- |
| Input | | Output | |
| Facilities | 4E-10 plant of chemical organic factory | Product | **fiber** |
| Materials | 1 kg composites | Byproducts | MJ electricity |
|  | kg waste plastic incineration | Emissions | Ecoinvent 3.4 |
| Energy | 14.94 MJ electricity per kg matrix |  |  |
|  | 11.78 MJ natural gas per kg matrix |  |  |
| Manpowera | 3.7×10-6 job |  |  |

1. Rogers J. G., Brammer J.G. Estimation of the production cost of fast pyrolysis bio-oil. *Biomass and Bioenergy*. 2012; 36: 208-217.

### Mechanical process

Table S6 lists the LCI data for recycling the bumper beam by using the mechanical process. The composites is cut into small pieces and then separated into two fractions. For 1 kg composites, around 54 wt% fiber and 29 wt% matrix go to the fine fraction () which is presumably sold as inert fillers.8

(S39)

(S40)

The others are left in the coarse fraction () which are incinerated to generate electricity. The generated electricity can be calculated as

(S40)

Table S4.6: LCI data for Mechanical Recycle Process

|  |  |  |  |
| --- | --- | --- | --- |
| Input | | Output | |
| Facilities | 2.5E-7 plant rolling mill | Product | **kg filler** |
| Materials | 1 kg composites | Byproducts | MJ electricity |
|  | kg waste plastic incineration | Emissions | Ecoinvent 3.4 |
| Energy | 0.66 MJ electricity |  |  |
| Manpower | 1.2×10-6 job (assumed) |  |  |

## Disposal

### Incineration with energy recovery

Table S7 lists the LCI data for the incineration of waste composite bumper beam. As the LCI data for the incineration of composites are not available in the databases or literature, the LCI data for the incineration of mixed plastic wastes from the Ecoinvent database is used here. The waste composites is combusted in the incinerator. The unburned ashes are collected and treated as wastes for landfill. The generated heat is collected and used to generate electricity. Thus, the generated electricity () can be calculated as

(S41)

Table S4.7: LCI Data for Incineration with Energy Recovery

|  |  |  |  |
| --- | --- | --- | --- |
| Input | | Output | |
| Facilities | / | Product | **MJ electricity** |
| Materials | 1 kg waste plastic incineration | Byproducts | / |
| Energy | / | Emissions | Ecoinvent 3.4 |
| Manpowera | 8.4×10-7 job |  |  |

1. <https://resource.co/article/construction-begins-dunbar-incinerator-10329>

### Landfill

Table S8 lists the LCI data for the sanitary landfill of composite bumper beam. Since the LCI data for landfilling specific composites is not available in the databases and literatures, the LCI data for sanitary landfill of waste plastic mixtures in the Ecoinvent database is simply used.

Table S4.8: LCI Data for Landfill

|  |  |  |  |
| --- | --- | --- | --- |
| Input | | Output | |
| Facilities | / | Product | / |
| Materials | 1 kg sanitary landfill of | Byproducts | / |
|  | waste plastic mixture | Emissions | Ecoinvent 3.4 |
| Energy | / |  |  |
| Manpowera | 1.9×10-7 job |  |  |

1. <http://www.legco.gov.hk/yr13-14/english/fc/pwsc/papers/p14-06e.pdf>

# Cost Coefficients for Life Cycle Costing in Composite Bumper Beam Example

Table S4.9: Cost Coefficients for Materials and Energy (i.e., and ) in Life Cycle Costing

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Materials | Price | | Materials | Price | |
| Acetic anhydridea | 12.5 | $/kg | Nitrogen, liquidf | 0.07435 | $/kg |
| Acetoneb | 1 | $/kg | Nylon 6b | 3 | $/kg |
| Acrylonitrileb | 1.15 | $/kg | Peatb | 0.2 | $/kg |
| Adipic acidb | 1.5 | $/kg | Phosphate fertilierb | 0.35 | $/kg |
| Aluminumb | 2 | $/kg | Phthalic anhydrideb | 1.3 | $/kg |
| Aluminum oxideb | 0.5 | $/kg | Potassium chlorideb | 0.65 | $/kg |
| Boric acid, anhydrous powderb | 0.85 | $/kg | Propylene glycolb | 1.5 | $/kg |
| Calciteb | 0.15 | $/kg | Quicklimeb | 0.1 | $/kg |
| Cementb | 0.05 | $/kg | Rock woolb | 0.5 | $/kg |
| Clayc | 0.001 | $/kg | Silica sandc | 0.001 | $/kg |
| Coald | 0.06 | $/kg | Silicone productb | 5 | $/kg |
| Copperb | 5 | $/kg | Sodium Chlorideb | 0.05 | $/kg |
| Crude Oile | 0.5 | $/kg | Sodium hydroxideb | 0.5 | $/kg |
| Ethylene glycolb | 0.5 | $/kg | Stainless steelb | 1.5 | $/kg |
| Fluorsparb | 0.4 | $/kg | Steamg | 0.01 | $/kg |
| Glassb | 0.02 | $/kg | Sulphuric acidb | 0.2 | $/kg |
| Ironb | 0.5 | $/kg | Tap waterh | 0.00125 | $/kg |
| Limeb | 0.15 | $/kg | Terephthalic acidb | 1.5 | $/kg |
| Loadingc | 1 | $/kg | Ureab | 0.15 | $/kg |
| Lubricating oilc | 1 | $/kg | Vinyl acetateb | 1 | $/kg |
| Organic chemical (assume methanol)b | 0.5 | $/kg |  |  |  |
| Energy | Price | | Energy | Price | |
| Biomassc | 0.001 | $/MJ | Electricityj | 0.0195 | $/MJ |
| Dieseli | 0.029 | $/MJ | Natural gask | 0.00368 | $/MJ |

1. <http://www.rightpricechemicals.com/buy-acetic-anhydride-reagent-acs.html>
2. <https://www.alibaba.com/>
3. Assumed
4. <http://markets.businessinsider.com/commodities/coal-price>
5. <http://www.infomine.com/investment/metal-prices/crude-oil/1-year/>
6. <https://hypertextbook.com/facts/2007/KarenFan.shtml>
7. <https://www.intratec.us/chemical-markets/steam-prices>
8. <http://cwf.ca/wp-content/uploads/2015/11/CWF_WaterBackgrounder8_SEP2011.pdf>
9. <https://www.globalpetrolprices.com/diesel_prices/>
10. <https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a>
11. <https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm>

Table S4.10: Cost Coefficients for the Facilities (i.e., ) in Life Cycle Costing

|  |  |  |
| --- | --- | --- |
| Life cycle stages | Facilities | Capital cost |
| Raw material production | Carbon fiber production planta | $1.25×108 per plant |
| Glass fiber product plantb | $1.35×107 per plant |
| Kenaf fiber production plantc | $4.6 per square land |
| Jute fiber production plantc | $4.6 per square land |
| Polyester resin production plantd | $3.3×106 per plant |
| Epoxy resin production plante | $3.2×107 per plant |
| Polypropylene production plantf | $2.07×108 per plant |
| Polyethylene production plantg | $2×108 per plant |
| Polyethylene terephthalate production planth | $1.9×108 per plant |
| Product manufacturing | Injection molding processb | $6×104 per plant |
| End of use | Pyrolysis processi | $9.4×106 per plant |
| Mechanical recycle processb | $1.5×104 per plant |
| Incineration process with energy recoveryj | $8.35×107 per plant |

1. <https://www.knoxnews.com/story/money/business/2016/10/12/lemond-composites-marks-opening-oak-ridge/91969622/>
2. Assumed
3. <http://usda.mannlib.cornell.edu/usda/current/AgriLandVa/AgriLandVa-08-03-2017.pdf>
4. <https://asia.nikkei.com/Markets/Nikkei-Markets/Malaysia-s-Luxchem-Expanding-Capacity-Aiming-10-Exports-Growth-Next-Year-Managing-Director>
5. <https://www.icis.com/resources/news/2003/05/07/195239/dow-starts-new-41-kt-yr-epoxy-resins-plant-in-china/>
6. <https://www.bizjournals.com/houston/news/2017/06/22/brazil-petrochem-co-to-build-675m-project-in.html>
7. <https://www.lyondellbasell.com/en/la-porte-complex/news/lyondellbasell-begins-construction-of-hyperzone-pe-plant-at-its-la-porte-complex/>
8. <http://www.chemicals-technology.com/projects/-mg-pet-plant-corpus-christi-texas/>
9. Rogers JG, Brammer JG. Estimation of the production cost of fast pyrolysis bio-oil*.* *Biomass and Bioenergy*. 2012;36:208-217.
10. <https://wteinternational.com/cost-of-incineration-plant/>

# Nomenclature

|  |  |  |
| --- | --- | --- |
| Symbol | Definition | Unit |
|  | Density | kg/m3 |
|  | Poisson’s ratio |  |
|  | Local stiffness matrix for *r*-th composite rod |  |
|  | Global stiffness matrix for *r*-th composite rod |  |
|  | Global stiffness matrix for composite bumper beam |  |
| , | Lower and upper bounds of variables |  |
|  | Product cost | $/unit product |
|  | Life cycle cost at *i*-th product life cycle stage | $ |
|  | Cost of input energy at *i*-th product life cycle stage | $ |
|  | Cost of input facility at *i*-th product life cycle stage | $ |
|  | Unit cost of *e*-th input energy | $/MJ |
|  | Capital cost of f-th input facility | $/plant |
|  | Unit cost of *m*-th input material | $/kg |
|  | Cost of input labor at *i*-th product life cycle stage | $ |
|  | Cost of input material at *i*-th product life cycle stage | $ |
|  | Collection rate of spent product |  |
|  | Life cycle environmental impact at *i*-th product life cycle stage | Pt |
| , | Young’s modulus in the *X-X* and *Y-Y* directions | GPa |
|  | Economic impact in product life cycle | Pt |
|  | Environmental impact of input energy at *i*-th life cycle stage | Pt |
|  | Environmental impact of emission at *i*-th life cycle stage | Pt |
|  | EES impact at end of use stage |  |
|  | EES impact at product use stage |  |
|  | EES impact at product manufacturing stage |  |
|  | EES impact at raw material production stage |  |
|  | Environmental impact of input facility at *i*-th life cycle stage | Pt |
|  | Environmental impact in product life cycle | Pt |
|  | Environmental impact of input material at *i*-th life cycle stage | Pt |
|  | Selection of J-th end-of-use strategy |  |
|  | Selection of *s*-th fiber (binary variable) |  |
|  | Government policy |  |
| *G* | Shear modulus of ingredients | GPa |
|  | Shear modulus in the *X-Y* direction | GPa |
|  | Consumer preferences |  |
| *HV* | Heating value | MJ/kg |
|  | Amount of *e*-th input energy at *i*-th product life cycle stage | MJ |
|  | Amount of *f*-th input facilities at *i*-th product life cycle stage | Piece of plant |
|  | Number of input labor headcount at *i*-th product life cycle stage | Jobs |
|  | Amount of *m*-th input material at *i*-th product life cycle stage | Kg |
|  | Spatial orientation |  |
|  | Spatial orientation |  |
|  | Spatial orientation |  |
|  | Selection of *k*-th matrix (binary variable) |  |
|  | Process design |  |
|  | Product disposal |  |
|  | Product quality |  |
|  | Social impact at *i*-th product life cycle stage |  |
|  | Supply chain |  |
|  | Fiber’s spatial orientation |  |
|  | Social impact in product life cycle |  |
|  | Product sustainability |  |
|  | Geometric strain transformation matrix of *r*-th composite rod |  |
|  | Technical requirements |  |
|  | Volume fraction |  |
|  | Average wage level | $/job/year |
|  | Ingredient selection |  |

# Literature Cited

1. Pastore CM, Gowayed YA. A self-consistent fabric geometry model: modification and application of a fabric geometry model to predict the elastic properties of textile composites*.* *Journal of Composites, Technology and Research*. 1994;16(1):32-36.

2. Vaidyanathan R, Gowayed YA. Optimization of elastic properties in the design of textile composites*.* *Polymer Composites*. 1996;17(2):305-311.

3. Vaidyanathan R, Gowayed YA, El-Halwagi M. Computer-aided design of fiber reinforced polymer composite products*.* *Computers & Chemical Engineering*. 1998;22(6):801-808.

4. Jones RM. *Mechanics of composite materials*. Second edition ed.: CRC press. 1998.

5. Miravete A. *3-D textile reinforcements in composite materials*. Woodhead Publishing. 1999.

6. Madan J, Mani M, Lee JH, Lyons KW. Energy performance evaluation and improvement of unit-manufacturing processes: injection molding case study*.* *Journal of Cleaner Production*. 2015;105:157-170.

7. Kim HC, Wallington TJ. Life-Cycle Energy and Greenhouse Gas Emission Benefits of Lightweighting in Automobiles: Review and Harmonization*.* *Environmental Science & Technology*. 2013;47(12):6089-6097.

8. Palmer J, Savage L, Ghita OR, Evans KE. Sheet moulding compound (SMC) from carbon fibre recyclate*.* *Composites Part A: Applied Science and Manufacturing*. 2010;41(9):1232-1237.