





## A Feature-based Physical-Geometric Model for Dynamic Effect in HVOF Thermal Spray Process

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### ABSTRACT

Thermal spray is a very versatile technology for improving surface performance in engineering. High velocity oxygen-fuel (HVOF) thermal spraying is an advanced thermal spraying technique with complex processes. It is a non-trivial research effort to create a computer model of the process with consideration of the multidisciplinary physical-geometric parameters. To deal with the challenge, a feature-based modeling method is proposed to establish the integrated framework on the dynamic physics of the coated substrate during the process with consideration of nozzle configurations, gas flow rate, and the torch path. For fulfilling this purpose, a novel HVOF spray physics feature model is presented to parametrically define the particle-gas jet. In addition, the torch path is developed to be a class of associative geometric feature with a proposed coupling mechanism between them. Dynamic physics of the substrate is investigated. A case study of the thermal history effect pattern of a substrate B-spline surface is illustrated to show the effectiveness of the proposed modeling method.

**Keywords:** HVOF thermal spray; Feature-based modeling; CFD; Torch path; Temperature history prediction

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### 1 INTRODUCTION

High velocity oxygen-fuel (HVOF) deposition is a kind of thermal spraying technologies protecting or improving the surface performance of a substrate or workpiece [24]. It is a complex physicochemical process involving chemical reaction, turbulence, compressible flow, multiphase interactions, subsonic/supersonic transitions, droplet deformation and solidification [14]. During the process, the thoroughly mixed fuel-oxygen gases (typically hydrocarbon-oxygen) and micro particles are fed into the gun chamber where a combustion reaction takes place. The fuel-oxygen combustion generates a hot-sonic/supersonic gas stream. Micro particles of metals, alloys or

cermets are accelerated and heated in the sonic/supersonic combusting gas stream and are deposited on a substrate at high speeds [22]. Typically, coating quality is influenced by many factors, like gun geometry, fuel/oxygen ratio, and particle sizes. In the past two decades, robots and other spray movement systems have been widely used to control the relative movement between spray torch and the substrate, which increases the complexity of the process. The parameters of spray distance, scanning velocity, and scanning step also have a significant impact on the coating properties [11]. Motivated by the intent of obtaining a high-quality coating, computational fluid dynamics (CFD) simulation has reached a high level of sophistication in the field of thermal spray process modeling to explore optimally operating setups. However, most simulation studies of HVOF only consider individual disciplinary aspects (e.g. geometric or torch path effects). To the authors' best knowledge, there have been no published literature on integrated modeling method which enables combine multidisciplinary characterization in an HVOF thermal spray process. Moreover, most previous researches aimed at improving coating quality indirectly via optimizing behaviors of the gas-particle jet from the nozzle [2],[13],[14],[20], instead of the most effective coating quality.

To overcome the problems, feature technology is used in this research to model the process and manage the multidisciplinary controlling parameters. In the past decades, feature-based modeling remains a hot spot in different aspects of engineering [29]. In the last few years, feature technology has been extended to multiple-view engineering modeling, such as chemical process and fluid-dynamic involved design process [16],[28]. As mentioned, the HVOF thermal spray process is a complex and multidisciplinary process. A feature-based model can maintain the information fusion and systematic data integration among different disciplinary domains, which can effectively address the information sharing requirements of HVOF modeling.

In this paper, the HVOF thermal spray process is modeled by implementing the concepts of CAE boundary feature [17], physics feature, associative geometric feature [21] and dynamic effect feature. For fulfilling this purpose, the correspondences between the real word control parameters and the simulation setup parameters are established. For gaining the dynamic behaviors of a developing coating process, a coupling mechanism is proposed to construct the link between the combustion flame jet behaviors and dynamic physics of a substrate coating. Finally, through applying feature technology, the effects of the chemical reaction, nozzle geometries and torch path on a substrate coating are integrated into the proposed modeling method. The dynamic behaviors of the coated substrate are simulated directly via CFD with varying controlling attributes in our proposed features. The paper is organized into the following sections. Section 2 investigates shortcomings of the current state of the art by reviewing related research works. The framework of the feature-based modeling is described in Section 3. An HVOF spray physics feature model is described in Section 4. In Section 5, a coupling mechanism embedded in an associative feature concept is introduced. In addition, the feature conversion for describing dynamic characteristics of the substrate is developed. Section 6 demonstrates the case study of the thermal history effect pattern of a substrate B-spline surface, which verified the mechanism of the proposed model.

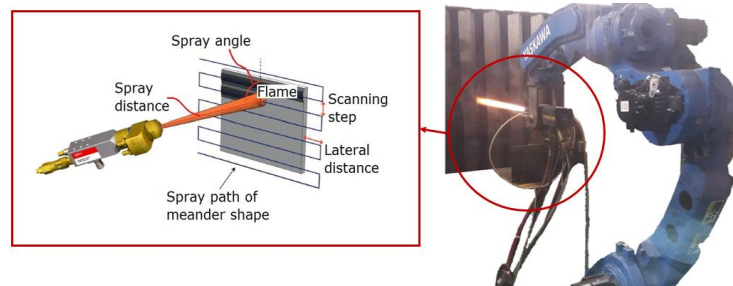
## 2 LITERATURE REVIEW

Thermal spray is a technology that involves a group of techniques and coating processes that improve the performance of a component surface functionality [8]. As introduced in [9], Dr. Max Ulrich Schoop and collaborators originated a series of thermal spray techniques and equipment enabling to melt and propel metals in the state of powder towards surfaces to forming a coating. In the late 1970s, a more advanced technique, HVOF, was developed based on flame spray, and so far, a big family of the combustion thermal spray techniques has been established.

However, exploring strategies for generating best-operating setups has been remaining a continuous challenge in the HVOF process. With the rapid development of computer-aided design/computer-aided engineering (CAD/CAE), virtual simulation has been widely used in the study of the process. Some researchers aiming to explore optimal operating parameters have

established different numerical models. Li and Christofides [13],[14] proposed a hybrid fundamental model for the physicochemical behaviors involved in the process via CFD. Their research results revealed the effects of chemical reaction in the nozzle chamber on in-flight behaviors of the particle-gas jet. In their work, chemical reaction was controlled by the mass flow rate of oxygen-fuel gases from inlet orifices and chemical-reaction numerical model was determined by particle-gas volume fraction and an iteration method they proposed [14],[20]. Based on their modeling system, an optimal equivalence ratio close to 1.2 for the propylene/oxygen/air flow rate was indicated. Baik et al. [2],[3] created a similar computational model to investigate the effect of nozzle shape on the in-flight performance of the particle-gas jet. They successfully used their research results to optimize the nozzle design. Their combustion models were both founded on propylene-oxygen chemistry. Pan et al. [23] built a liquid-fueled HVOF model with kerosene-fueled chemistry and analyzed the effects of particle diameter, particle shape and particle injection velocity on the in-flight particle behavior. Through investigating previous research efforts, several consensus can be reached: (1) ANSYS/FLUENT [27] has been a powerful tool to simulate an HVOF process; (2) FVM (finite volume method) with SIMPLE algorithm is solved for the pressure, velocity and temperature distributions in the process; (3) Due to the time consumption caused by the highly turbulent compressible flow in the process, the Boussinesq hypothesis is made to represent the Reynolds stresses with the mean velocity gradients; (4) The RNG  $k-\epsilon$  turbulence model is used with the non-equilibrium wall function treatment to enhance the prediction of the wall shear and heat transfer; (5) The eddy-dissipation model is employed to describe the reaction rate; (6) The stochastic tracking approach in ANSYS/FLUENT enables to describe the turbulent dispersion of particles. In their approaches, only single-disciplinary parameters were analyzed, however, the dynamic behaviors of a coating simultaneously affected by multi-disciplinary parameters were ignored. Moreover, some kinematic factors (e.g. scanning velocity, scanning step and spray distance) in the industrial process were neglected.

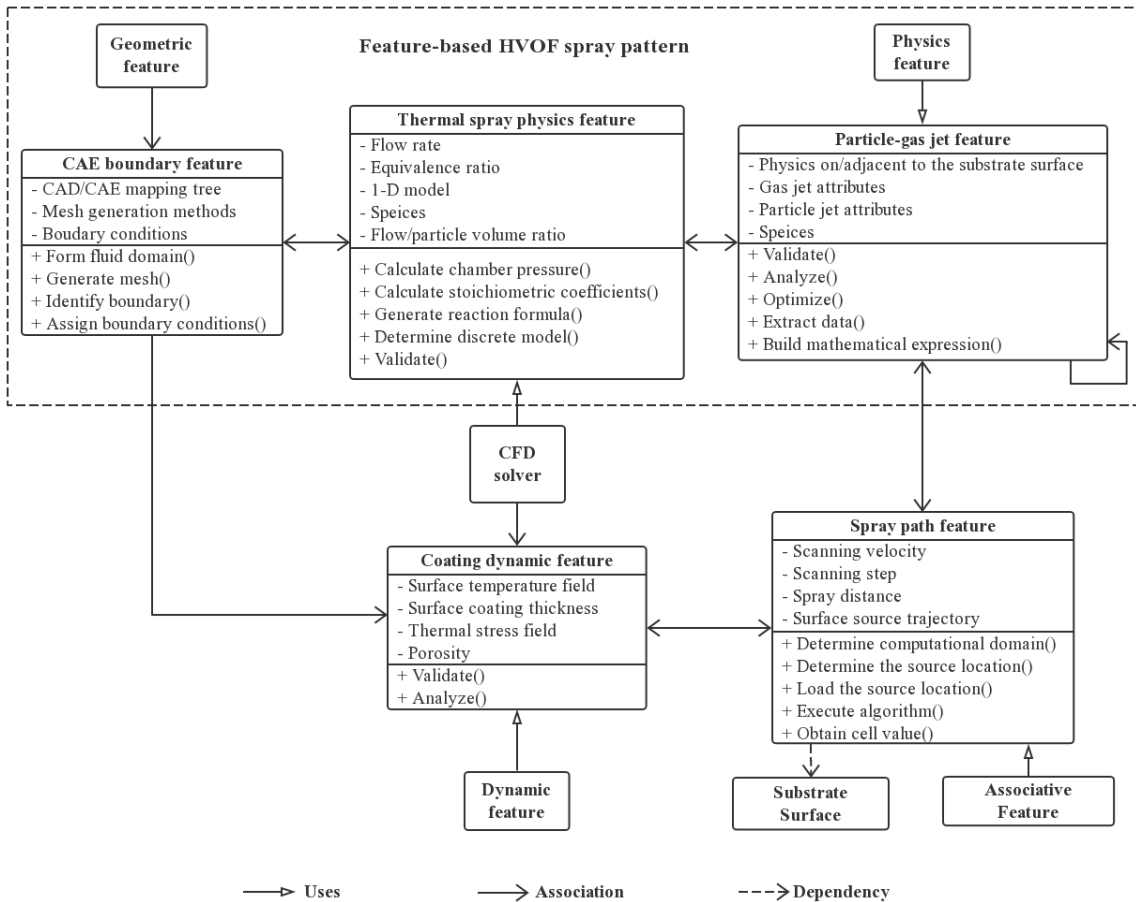
In contemporary manufacturing, robots and handling systems have been developed to control the movement of the spray torch relative to the substrate, which results in some kinematic parameters that have a significant impact on the coating quality. The main kinematic parameters are the spray angle, scanning velocity and spray path as shown in Figure 1 [11]. To explore the effects of the kinematics, several research teams proposed numerical models for robot-guided thermal spraying processes. Bolot et al. [1] constructed a coupled model between robot trajectories and dynamic behaviors of the substrate. The proposed model read a text file containing the real robot trajectory and solved the transient heat conservation equation during torch displacement. However, the spray jet pattern (behaviors of the in-flight jet) in their model was limited to their specific operating setups. Thus, their model is not generally compatible with different gun nozzle configurations and input setups. Candel and Gadaw [4],[10] presented an idea to remedy the shortcoming in Bolot's model. CFD tools were adopted in their approach to create the spray physical model so that the parameters of nozzle configurations and fuels flow rates could be taken into account in the process simulation, but the approach combining the CFD spray model with torch trajectories is not systematic.



**Figure 1:** Robot-guided thermal spraying and main kinematic parameters.

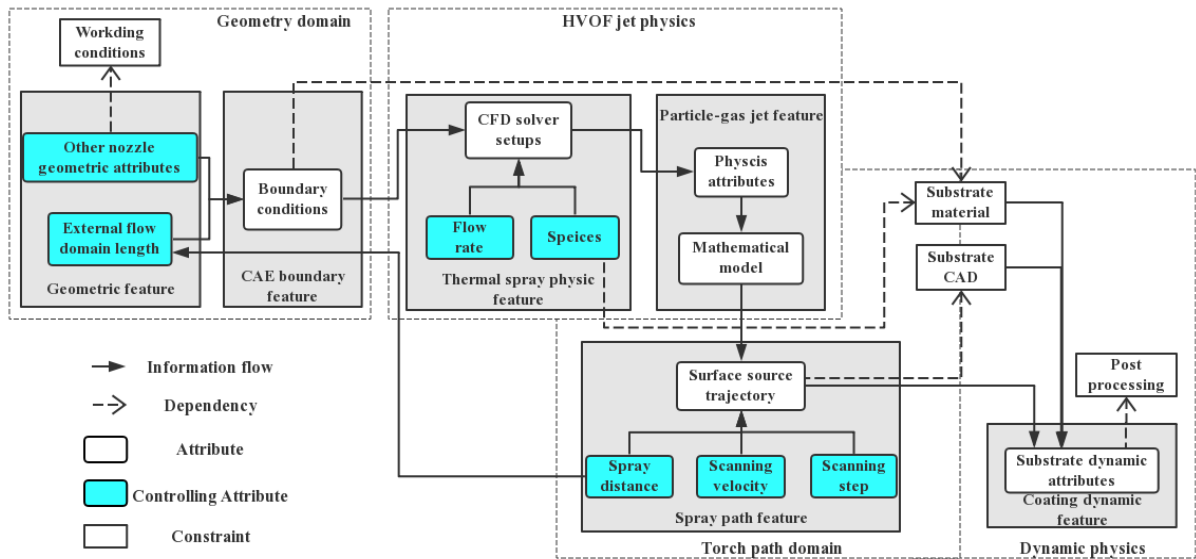
### 3 FRAMEWORK OF THE FEATURE-BASED MODELING

The proposed feature-based modeling considers four major domains in the HVOF process, geometries, jet physics, the torch path and dynamic physics of the substrate. As to this article’s focus of multidisciplinary-parametric modeling, in order to keep the information consistency in different process stages and facilitate the correspondence between the real world processes and simulation models, the whole process is modeled in terms of *CAE boundary feature* [19] and four new feature concepts, *thermal spray physics feature*, *particle-gas jet feature*, *spray path feature* and *coating dynamic feature* which are specific for the thermal spraying process. The entities and parameters involved in the four domains are converted to attributes in the feature concepts as shown in Figure 2. The attribute relationships among the features are developed to be abstracted associations, which supports information sharing. The structure and associations in the proposed modeling method are depicted in Figure 2 as well.



**Figure 2:** UML diagram representing the semantic model framework.

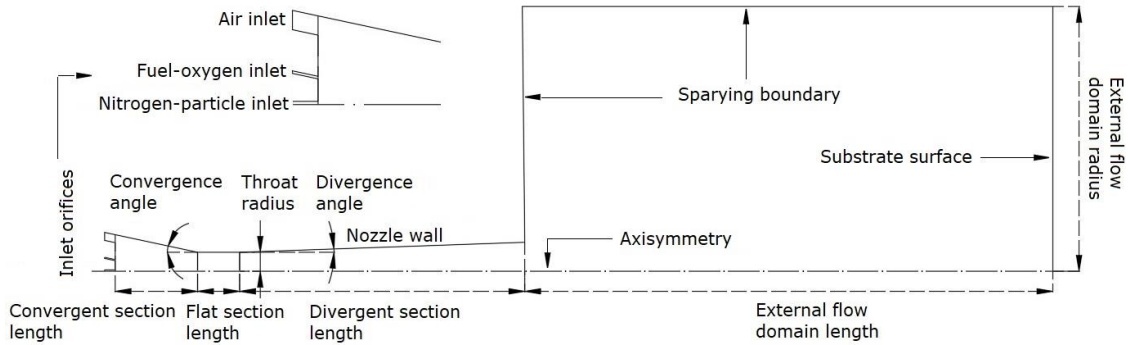
Figure 3 further indicates the semantic relationships and information flow in our proposed modeling method. For example, the external flow domain length in the CAE boundary feature will be changed when the spray distance in the spray path feature is adjusted. The implements of the semantic relationships are explained in Section 4 and Section 5. By the feature-based parametric mean, this complex process can be controlled by the controlling attributes in the four domains.



**Figure 3:** Relations in the feature-based model.

#### 4 HVOF SPRAY PHYSICS FEATURE MODEL

HVOF spray pattern is defined to describe the combustion in the nozzle chamber and the flame jet [1]. According to the review of related literature, nozzle configurations and fuel-oxygen flow rates from inlet orifices play crucial roles in the computational model of the combustion and flame jet. The geometric entities involved in the nozzle configurations are traditionally represented by CAD model. However, the lack of consistent modeling of physics and geometrical feature associations causes the isolation of design intent limited to fixed geometries. In other words, the missing of semantic information on engineering working principles, constraints and related behaviors in the nozzle model and analysis impedes the overall HVOF process optimization. To achieve the fully digital virtual physics simulation with design changes, the frequent conversion between CAD models and CAE setups is necessary so that the cyclic CAE analysis results can be constantly considered [18]. To bridge this gap, a comprehensive mechanism needs to be proposed for parametrically controlling the nozzle configurations. Li et al. [19] proposed a new feature based on the concept of associative feature, called CAE boundary feature, which fulfills a seamless CAD/CAE integration. In our research, the CAE boundary feature is used to assist the creation of a CAE spray physical model carrying physical behaviors of the combustion and the flame jet. The major function of the CAE boundary feature used helps to implement the conversion mechanism between the geometric entities in the spray pattern and boundary condition setups in the CAE model, such as the determination of the fluid domain and CAE configurations for a specified spray gun. Figure 4 shows the major geometric entities in the spray pattern and Table 1 offers the partial mapping relationships which are embedded in the CAE boundary feature. In this way, the CAE boundary condition setups could be automatically completed without redundant model preparations when the geometries are changed.



**Figure 4:** Major geometric entities in the spray pattern.

<i>Attribute</i>	<i>Semantic information</i>	<i>Boundary condition in CAE</i>
Inlet orifices	Inlet orifices of the fuel gases and particles; Defining the feed velocity or pressure.	Velocity/pressure inlet
Spraying boundary	The boundary for external flow domain.	Pressure outlet
Nozzle wall	Nozzle wall; Cooling type.	No-slip wall
Substrate surface	Substrate surface.	No-slip wall
Convergent/flat/divergent section length	Nozzle shape entities.	Axis
External flow domain length	Spray distance.	Axis
Convergent section	Combustion chamber.	Computational domain for the combustion

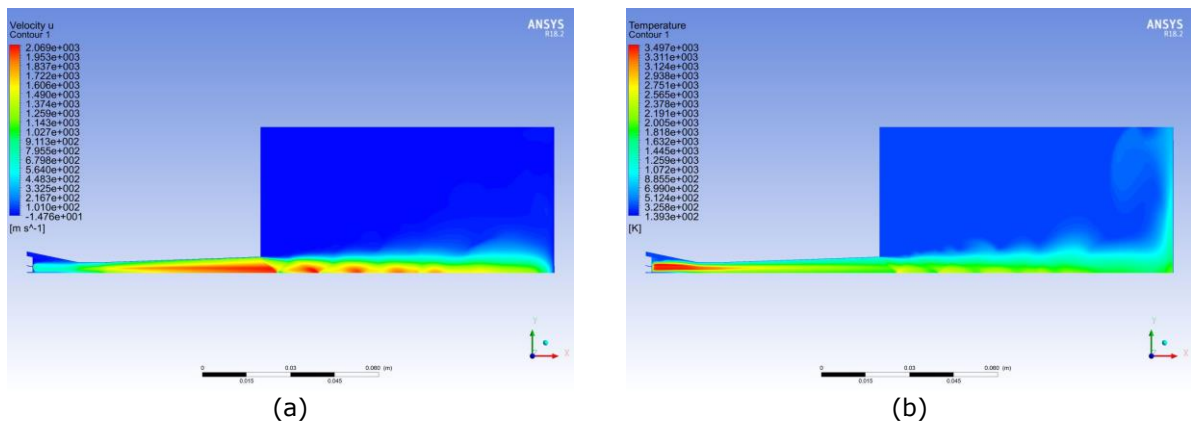
**Table 1:** The relations between the geometric entities in the spray pattern and CAE boundary condition in the CAE model.

Commonly, CFD tools require not only explicit geometry inputs and boundary condition setups but also complicated solver setups. For facilitating an automatic process of the solver setups for the simulation of the spray pattern in a CFD environment, thermal spray physics feature is defined as an object class with rules for obtaining the setup parameters. As discussed in the literature review, some consensus for the setups of a CAE spray physical model has been reached, but the solver setups for the combustion and the particle-flow interaction are tricky. Actually, the solver setup for the combustion needs a precise reaction formula depending on the fuel-oxygen mass flow rate and the reaction pressure. In industry, the oxygen-fuel flow rate could be read through the inlet valves. However, the combustion pressure in the chamber is difficult to be tracked directly. In the proposed modeling, the reaction pressure is approximately calculated based on the oxygen-fuel flow rate (or equivalence ratio) via several iterations [14], which is a function embedded in the feature concept. Once the reaction pressure is obtained, the stoichiometric coefficients for the predefined flow rates can be determined. In terms of the particle-flow interaction model, the gas/particle volume fraction enables to determine the solver setup. Consequently, some key attributes must be contained in the thermal spray physics feature to support the feature functions, such as equivalence ratio, reaction species, and flow/particle volume ratio.

After formulating the solver setups, all physics behaviors of the combustion and the jet could be exported from the simulation results. To apply the results to the down-stream process, particle-gas jet feature is proposed to manage the static physics behaviors of the combustion and the jet.



This proposed feature primarily works as an interface for the down-stream of the model so that the data stored in the CAE spray physical model become available for the following steps. For implementing the function, physics adjacent to and on the substrate surface is abstracted as attributes in this feature. In a simulation case, the attributes could be the temperature and pressure field of the reactive flow adjacent to the substrate surface, as well as heat flux and particle deposition distribution on the substrate surface. Usually, this attribute needs to be further developed to be a mathematically abstracted source model which will be attached to the torch path for computing the corresponding dynamic physics of the substrate. This point is introduced in the next section. In addition, the particle-gas jet feature also provides the functions of validating and improving the parameters for the spray pattern via dealing with attributes of gas/particle jet physics and species respectively. The semantic associations in the proposed spray physical model are represented by using a UML diagram as shown in Figure 2. Consequently, an HVOF spray physics feature model can be built completely according to the process. Figure 5 shows examples of attributes exported from the HVOF spray physics feature model in the environment of ANSYS/Fluent.



**Figure 5:** Examples of jet physics from a case of 100mm spray distance: (a) Axial velocity distribution and (b) temperature distribution.

## 5 COUPLING MECHANISM

### 5.1 Feature concepts in the coupling mechanism

In industry, the coating process guided by a handling system is a dynamic process. The transient physics of the substrate during the torch movement has a significant impact on the coating properties. In order to capture the dynamic physics in the simulation model, a coupling mechanism must be established, which enables to associate the simulation results from the HVOF spray physics feature model with the torch trajectory. Meanwhile, to be consistent with the trend in this field, the proposed method should have the capacity to analyze the effects of the torch trajectory on dynamic physics. To achieve these two purposes, besides the particle-gas jet feature concept, two new features which are specific for the thermal spraying process, namely spray path feature and coating dynamic feature, are proposed to manage the entities and associations involved here. The coating dynamic feature is based on the dynamic feature concept. Like the concept of the particle-gas jet feature, the coating dynamic feature works as interface protocol as well in this method. Instead of providing information as the particle-gas jet feature, the coating dynamic feature receives the information transferred from the spray path feature and converts to the

corresponding dynamic features. The attributes in the coating dynamic feature are shown in Figure 2.

## 5.2 Implementation of the coupling mechanism

In industry, a spray path describes the relative movement between the torch and the coating substrate. In a simulation system, a spray pattern moving along a predefined path acts on a coated surface to deposit semi-molten particles. Therefore, the spray path is the key in the completeness of the coupling mechanism. In our proposed modeling method, spray path is developed to be a class of associative feature, called spray path feature that contains the mapping relations between the physics of the particle-gas jet and the corresponding dynamic physics of the substrate surface. In this concept, the spray paths are abstracted into smart lines associated with attributes for generating the torch trajectories.

The ultimate goal of the spray path feature is to generate trajectories of HVOF flame center point on the substrate surface. Some research works have been dedicated to torch trajectory generation based on parameters of scanning velocity, scanning step, spray distance, spray angle, and surface normal [5-7],[26]. After obtaining the torch trajectories, the mapping trajectories which are defined as the movement of the HVOF flame center on the substrate surface can be obtained via the torch orientation as shown in Figure 6(a). In this paper, the spray angle between the torch orientation and the tangent plane of the substrate surface is always assumed to be orthogonal to ensure high-quality coatings [4]. For simplification, the flame center trajectories on the substrate surface are intuitively described as surface source trajectories, which distinguishes torch trajectories. The physical properties of the particle-gas jet feature have a rotational-symmetry characteristic due to the axisymmetric shape of the spray gun. Theoretically, such properties can be modeled by a mathematical function of the radial distance from the center point of the flame through extracting data from the particle-gas jet feature. Once the mathematical model is established, an instantaneous physical property applied on each cell surface could be obtained through calculating the distance from each cell location to the corresponding instantaneous surface source center as shown in Figure 6(b).

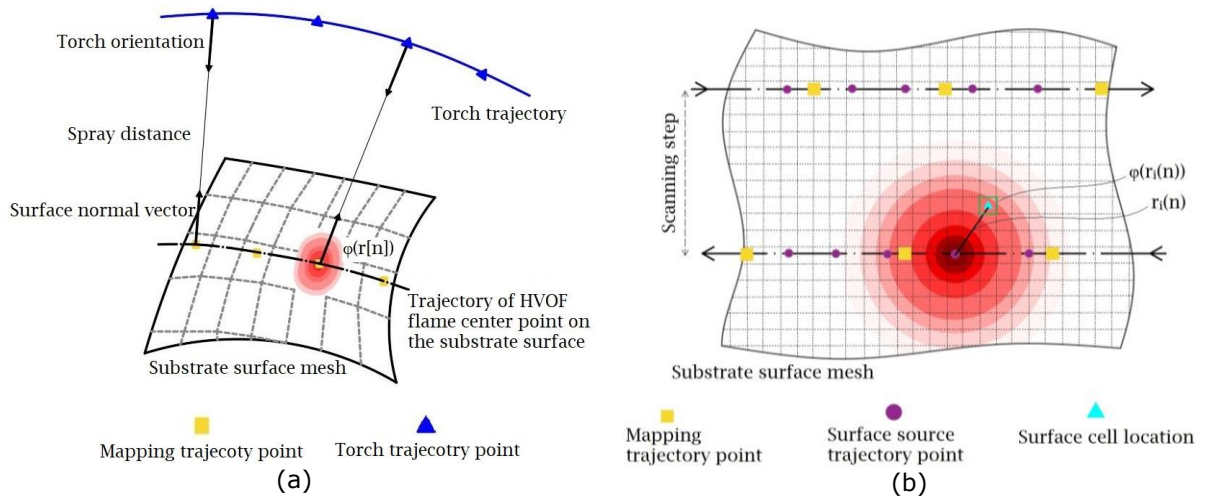
However, the time step in CFD tools may be different from the time interval between torch trajectory points. To overcome this barrier, a FORTRAN subroutine was programmed to calculate the surface source trajectory points at the time steps in CFD tools. Due to the extremely short distance and the time interval between two adjacent torch trajectory points, the torch movement between the two adjacent points is assumed to be uniform-rectilinear. According to the above approximation process, the surface source trajectory points at the time steps in CFD tools can be calculated by Equation (5.1), and then the instantaneous physical property applied on each cell surface is calculated by Equation (5.2):

$$\mathbf{X}_S(i) = \mathbf{X}_M(k) + \frac{t_T(k+1) - t_T(k)}{t(i) - t_T(k)} \cdot [\mathbf{X}_M(k+1) - \mathbf{X}_M(k)], \quad t_T(k+1) < t(i) \leq t_T(k) \quad (5.1)$$

$$\varphi(r_i(n)) = \varphi \|\mathbf{X}_C(n) - \mathbf{X}_S(i)\| \quad (5.2)$$

where  $\mathbf{X}_S(i)$  is the flame center location on the substrate surface at the  $i^{\text{th}}$  time step in CFD tools,  $\mathbf{X}_M(k)$  is the location of the  $k^{\text{th}}$  mapping trajectory point,  $\mathbf{X}_C(n)$  is the location of the  $n^{\text{th}}$  surface cell,  $t_T(k)$  is the time corresponding to the  $k^{\text{th}}$  torch trajectory point,  $t(i)$  is the time at the  $i^{\text{th}}$  CFD time step and  $\varphi(r_i(n))$  is a physical property applied on the  $n^{\text{th}}$  surface cell at the  $i^{\text{th}}$  CFD time step. With this treatment, the source center can move with CFD time steps to obtain a dynamic physics field of the substrate surface that is received and stored in the coating dynamic feature for potential post-processing and optimization.





**Figure 6:** (a) Trajectories of HVOF flame center point on the substrate surface, (b) Surface source trajectory.

## 6 CASE STUDY

### 6.1 Thermal history of a substrate B-spline surface

The temperature of a coated substrate during the process has critical effects on the coating quality and the properties of the substrate. Ideally, the temperature of the reactive flow must be high enough to melt the metallic bonding material around particles and a substrate heated by the jet should have a low and uniform temperature field to avoid material degradations and thermal stresses [5],[20]. Therefore, predicting and controlling the thermal history of the substrate is crucial for the process.

The application of the proposed feature-based modeling scheme was demonstrated by the following case study of the thermal history effect pattern of a B-spline substrate for the gas jet only (no particle spray, just the reactive flow). The mechanism of the modeling was operated in the environment of ANSYS/FLUENT. The association function of the spray path feature was implemented by Visual C in ANSYS/FLUENT, including torch trajectory loading, surface source trajectory calculation, and mathematically abstracted source model loading. The geometric parameters for the thermal spray gun are listed in Table 2 [14]. The external flow domain length corresponding to the spray distance as shown in Figure 7 is 100.00 mm and the external flow domain radius is 50.00 mm which is much greater than the radius of the torch exit. The temperature of the nozzle wall during the process is always assumed as 300 K. The material setup for the wall at the right end of the external flow domain always keeps consistent with the substrate material. Based on the aforementioned CAE boundary feature concepts, the boundary condition setups for the jet simulation were completed. Here, respecting the computational time and convergence problems, the temperature boundary for the wall was set up as a constant temperature of 300 K. Although the substrate surface temperature is changing with the spray process, the variation of the temperature is much small when compared with the temperature of the adjacent flame. Thus, the substrate surface was treated as a constant temperature and the influence of the variable temperature on the flux transfer was ignored.

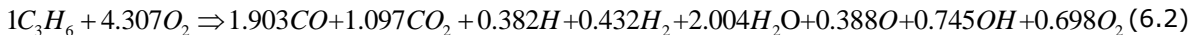
<i>Tag</i>	<i>Value</i>
Convergent section length	15.60 mm
Convergence angle	12.00 degree
Flat section length	7.95 mm
Throat radius	7.16 mm
Divergence angle	2.00 degree
Divergent section length	54.00 mm
External flow domain length	100.00mm
External flow domain radius	50.00 mm

**Table 2:** Thermal spray gun geometries.

In this case study, the combustion in the HVOF thermal process was described by a one-step propylene-oxygen reaction developed by Gordon and McBride [25].



where  $x$  is the number of moles of oxygen that react with one mole of propylene. To accurately model the combustion process, the products of combustion were assumed to dissociate into a number of species with low molecular weight,  $CO_2$ ,  $H_2O$ ,  $CO$ ,  $H_2$ ,  $OH$ ,  $H$  and  $O$ , due to the high reaction temperature [2]. The gas flow rates of propylene, oxygen, air and carrier gas (nitrogen) referred to [14] are listed in Table 3. As mentioned in the thermal spray physics feature, the reaction formula at this equivalence ratio was calculated via the iterative method [14] described above:



<i>Propylene (scfh)</i>	<i>Oxygen (scfh)</i>	<i>Air (scfh)</i>	<i>Nitrogen (scfh)</i>	<i>Equivalence ratio</i>
176	578	857	28.5	1.045

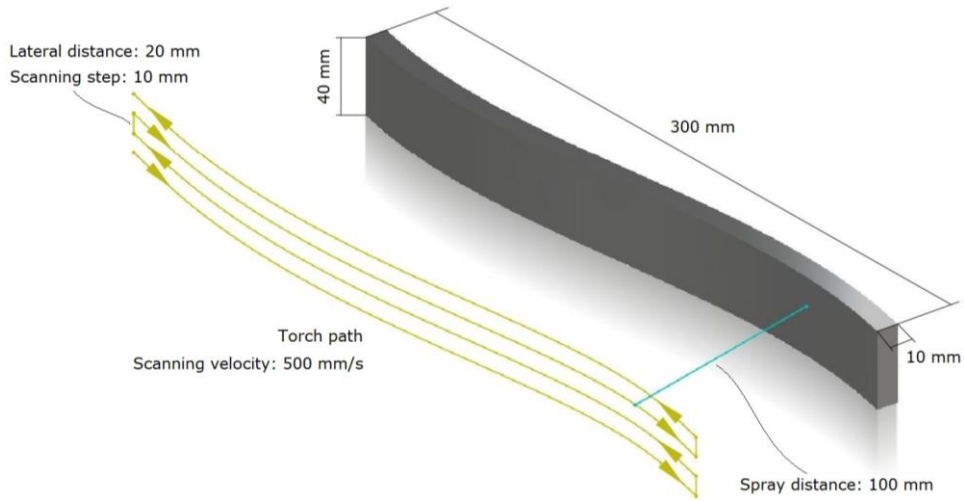
**Table 3:** Specified gas flow rate.

As the particle influence was not considered in this case, the interaction solver setups were skipped. After configuring the solvers, the heat flux transferred to the wall at the spray distance of 100 mm was extracted from the wall properties of the simulation results which are the attributes in the particle-gas jet feature. After then, a mathematical representation of the heat flux was modeled via the curve fitting of Gaussian distribution with 95% confidence bounds:

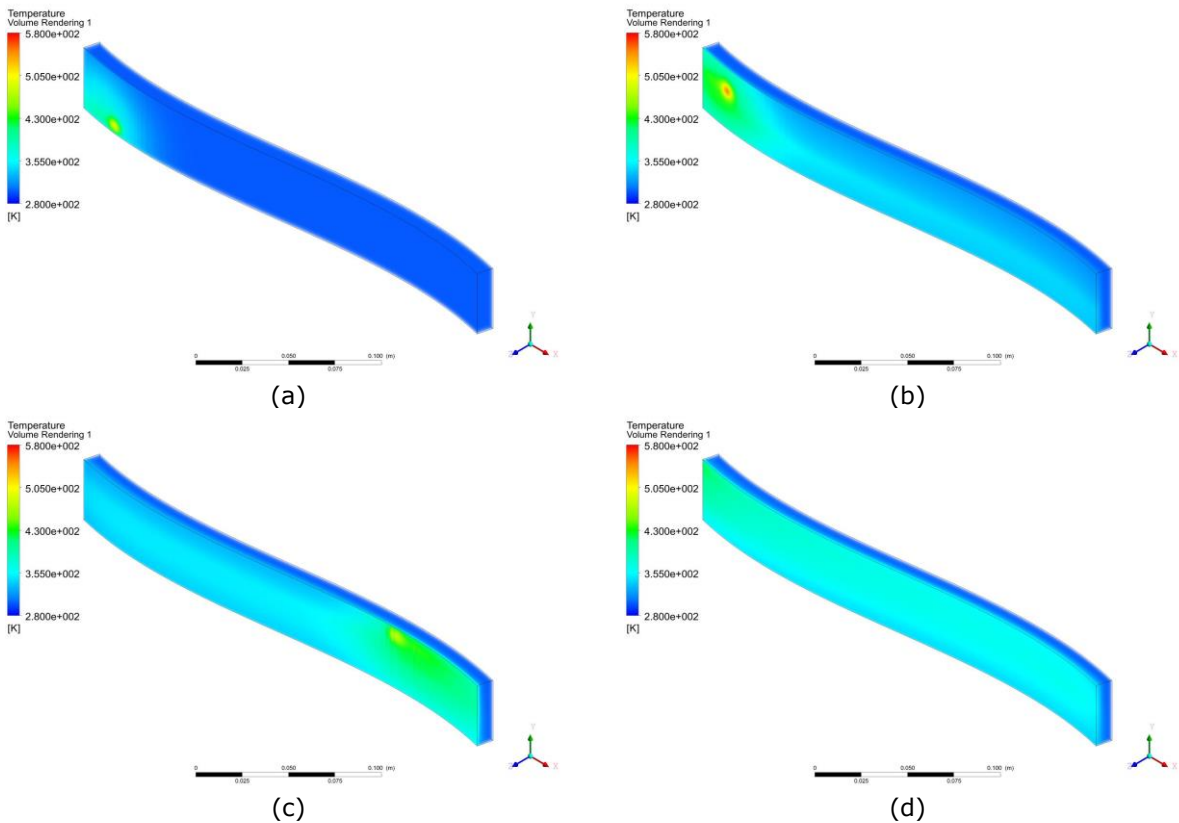
$$f(r) = a_1 * \exp(-((r - b_1) / c_1)^2) + a_2 * \exp(-((r - b_2) / c_2)^2) \quad (6.3)$$

where,  $a_1=4.388e+06$  (4.363e+06, 4.414e+06),  $b_1=-1.725e-15$  (-2.296e-05, 2.296e-05),  $c_1=0.005226$  (0.005188, 0.005265),  $a_2=1.914e+06$  (1.899e+06, 1.929e+06),  $b_2=5.122e-14$  (-0.0001391, 0.0001391),  $c_2=0.03497$  (0.03471, 0.03522).

The surface source trajectory was derived from the primal attributes as shown in Figure 7. A dynamic temperature field of the substrate was computed by combining the above mathematical model with the surface trajectory, which is described in the function of the spray path feature in detail. Figure 8 shows the computed substrate temperature field at four different times under the conditions of the predefined conditions. The maximum temperature during the dynamic process is 560 K around 1.5 s.



**Figure 7:** Schematic representation of the torch path and the substrate.



**Figure 8:** The dynamic temperature field of the substrate: (a) Transient temperature field at 0.1 s, (b) Transient temperature field at 1.5 s, (c) Transient temperature field at 2.3 s, and (d) Transient temperature field at 2.8 s.

## 6.2 Future development outlook

The torch orientation angle is not considered in the above case study, because the heat flux transferred to the surface is slightly affected by it. However, the torch orientation has a significant impact on other properties, like coating thickness. Besides, the proposed coupling mechanism is not available for sharp-shape substrate surfaces, because the mathematical model of the physical properties is established based on a flatten substrate surface. To overcome the barriers, in future works, the coupling mechanism can be further described in the cylindrical coordinate and the substrate surface geometry in the spray pattern can associate with the geometries in the substrate CAD model.

As reviewed in the recent articles, a concern for future research work is to explore strategies for generating optimal configurations. The proposed model was established by using the parametric feature modeling method allowing explicit change propagation and systematic tracking. Therefore, the effect analysis of controlling attributes is feasible in the method. In future works, the effect analysis process can be incorporated into the modeling by applying the method introduced in [19], which provides a potential way to facilitate a cyclic modeling system. Once the cyclic information flow is completed, optimization methodology [12],[15] can be leveraged in the post processing to determine optimal configurations.

## 7 CONCLUSIONS

In this paper, the HVOF thermal spray process is modeled in terms of four major domains, geometry, HVOF jet physics, torch path, and dynamic physics of the substrate. The entities involved in each domain are classified and modeled by feature technology so that the complex relationships among the entities are generically defined and could be managed in future programming implementation. For obtaining and controlling dynamic behaviors of a substrate, the spray path feature with a coupling mechanism is proposed to fulfill the link between an HVOF spray physics feature model and spray paths. In turn, the behaviors of the substrate surface can be parametrically controlled.

The effectiveness of the proposed modeling method has been demonstrated by a case study of the thermal history effect pattern of a substrate B-spline surface. Through configuring specified nozzle geometries and gas flow rates in the proposed HVOF spray physics feature model, the particle-gas jet physics model was established in the environment of ANSYS/Fluent. The dynamic thermal field of the substrate was virtually tracked under given spray conditions via the implementation of the proposed coupling mechanism.

The proposed physics-geometry coupling mechanism has not been well established yet for real production situation, e.g. considering sharp-shape surfaces and the torch orientation angle. To overcome future application barriers, the coupling mechanism will be further developed, and possibly, described in a cylindrical coordinate system. The feature-based modeling method will be further developed to respect strategies for generating optimal configurations.

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## REFERENCES

- [1] Bolot, R.; Deng, S.; Cai, Z.-H.; Liao, H.-L.; Montavon, G.: A coupled model between robot trajectories and thermal history of the workpiece during thermal spray operation, *Journal of Thermal Spray Technology*, 23(3), 2014, 296–303. <https://doi.org/10.1007/s11666-013-0048-z>
- [2] Baik, J.-S.; Kim, Y.-J.: Effect of nozzle shape on the performance of high velocity oxygen-fuel thermal spray system, *Surface and Coatings Technology*, 202(22-23), 2008, 5457-5462. <https://doi.org/10.1016/j.surfcoat.2008.06.061>
- [3] Baik, J.-S.; Park, S.-K.; Kim, Y.-J.: A numerical study on gas phase dynamics of high-velocity oxygen fuel thermal spray, *Japanese Journal of Applied Physics*, 47(8), 2008, 6907–6909. <https://doi.org/10.1143/JJAP.47.6907>
- [4] Candel, A.; Gadow, R.: Trajectory generation and coupled numerical simulation for thermal spraying applications on complex geometries, *Journal of Thermal Spray Technology*, 18(5-6), 2009, 981-986. <https://doi.org/10.1007/s11666-009-9338-x>
- [5] Cai, Z.-H.; Qi, B.-H.; Tao, C.-Y.; Luo, J.; Chen, Y.-P.; Xie C.-J.: A robot trajectory optimization approach for thermal barrier coatings used for free-form components, *Journal of Thermal Spray Technology*, 26(7), 2017, 1651-1658. <https://doi.org/10.1007/s11666-017-0601-2>
- [6] Chen, H.-P.; Sheng, W.-H.; Xi, N.; Song, M.-M.; Chen, Y.-F.: Automated robot trajectory planning for spray painting of free-form surfaces in automotive manufacturing, *Proceedings 2002 IEEE International Conference on Robotics and Automation*, 2002, 450–455. <https://doi.org/10.1109/ROBOT.2002.1013401>
- [7] Deng, S.-H.; Cai, Z.-H.; Fang, D.-D.; Liao, H.-L., Montavon, G: Application of robot offline programming in thermal spraying, *Surface and Coatings Technology*, 206(19-20), 2012, 3875–3882. <https://doi.org/10.1016/j.surfcoat.2012.03.038>
- [8] Espallargas, N.; Introduction to thermal spray coatings, *Future Development of Thermal Spray Coatings: Types, Designs, Manufacture and Applications*, Elsevier, Cambridge, England, 2015. <https://doi.org/10.1016/B978-0-85709-769-9.00001-4>
- [9] Fauchais, P.; Vardelle, A.; Dussoubs, B.: Quo vadis thermal spraying?, *Journal of Thermal Spray Technology*, 10(1), 2001, 44–66. <https://doi.org/10.1361/105996301770349510>
- [10] Gadow, R.; Candel, A; Floristán, M.: Optimized robot trajectory generation for thermal spraying operations and high quality coatings on free-form surfaces, *Surface and Coatings Technology*, 205(4), 1074–1079. <https://doi.org/10.1016/j.surfcoat.2010.08.121>
- [11] Gadow, R.; Floristán, M.: Manufacturing engineering in thermal spraying by advanced robot systems and process kinematics, *Future Development of Thermal Spray Coatings: Types, Designs, Manufacture and Applications*, Elsevier, Cambridge, England, 2015. <https://doi.org/10.1016/B978-0-85709-769-9.00011-7>
- [12] Hegels, D.; Wiederkehr, T., Müller, H.: Simulation based iterative post-optimization of paths of robot guided thermal spraying, *Robotics and Computer-Integrated Manufacturing*, 35, 1–15. <https://doi.org/10.1016/j.rcim.2015.02.002>
- [13] Li, M.-H.; Christofides, P.-D.: Computational study of particle in-flight behavior in the HVOF thermal spray process, *Chemical Engineering Science*, 61(19), 2006, 6540-6552. <https://doi.org/10.1016/j.ces.2006.05.050>
- [14] Li, M.-H.; Christofides, P.-D.: Multi-scale modeling and analysis of an industrial HVOF thermal spray process, *Chemical Engineering Science*, 60(13), 2005, 3649–3669. <https://doi.org/10.1016/j.ces.2005.02.043>
- [15] Li, L.; Cheng, Z.-R.; Lange, C.-F.: CFD-based optimization of fluid flow product aided by artificial intelligence and design space validation, *Mathematical Problems in Engineering*, 2018, 2018, 1–14. <https://doi.org/10.1155/2018/8465020>
- [16] Li, L.; Lange, C.-F.; Ma, Y.-S.: Artificial intelligence aided CFD analysis regime validation and selection in feature-based cyclic CAD/CFD interaction process, *Computer Aided Design and Applications*, 15(5), 2018, 643-652. <https://doi.org/10.1080/16864360.2018.1441230>

- [17] Li, L.; Lange, C.-F.; Ma, Y.-S.: Association of design and computational fluid dynamics simulation intent in flow control product optimization, *Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture*, 232(13), 2018, 2309-2322. <https://doi.org/10.1177/0954405417697352>
- [18] Li, L.; Lange, C.-F.; Xu, Z.; Jiang, P.-Y.; Ma, Y.-S.: Feature-based intelligent system for steam simulation using computational fluid dynamics. *Advanced Engineering Informatics*, 38, 2018, 357–369. <https://doi.org/10.1016/j.aei.2018.08.011>
- [19] Li, L.; Ma, Y.-S.: CAD/CAE associative features for cyclic fluid control effect modeling. *Computer Aided Design and Applications*, 13(2), 2016, 208–220. <https://doi.org/10.1080/16864360.2015.1084190>
- [20] Li, M.-H.; Shi, D.; Christofides, P.-D.: Diamond jet hybrid HVOF thermal spray: gas-phase and particle behavior modeling and feedback control design. *Industrial & Engineering Chemistry Research*, 43(14), 2004, 3632–3652. <https://doi.org/10.1021/ie030559i>
- [21] Ma, Y.-S.; Tong, T.; Associative feature modeling for concurrent engineering integration, *Computers in Industry*, 51(1), 2003, 51–71. [https://doi.org/10.1016/S0166-3615\(03\)00025-3](https://doi.org/10.1016/S0166-3615(03)00025-3)
- [22] Oberkampf, W.-L.; Talpallikar, M.: Analysis of a high-velocity oxygen-fuel (HVOF) thermal spray torch part 1 : numerical formulation, *Journal of Thermal Spray Technology*, 5(1), 1996, 53-61. <https://doi.org/10.1007/BF02647519>
- [23] Pan, J.-J.; Hu, S.-S.; Yang, L.-J.; Ding, K.-Y.; Ma, B.-Q.: Numerical analysis of flame and particle behavior in an HVOF thermal spray process, *Materials & Design*, 96, 2016, 370–376. <https://doi.org/10.1016/j.matdes.2016.02.008>
- [24] Pierlot, C.; Pawlowski, L.; Bigan, M.; Chagnon, P.: Design of experiments in thermal spraying: a review, *Surface and Coatings Technology*, 202(18), 2008, 4483–4490. <https://doi.org/10.1016/j.surfcoat.2008.04.031>
- [25] Gordon, S.; McBride, B.-J.: *Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks and Chapman–Jouguet Detonations*, National Aeronautics and Space Administration, Washington, D.C., 1976.
- [26] Sheng, W.-H.; Xi, N.; Song, M.-M.; Chen, Y.-F.; Macneille, P.: Automated CAD-guided robot path planning for spray painting of compound surfaces, *Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2000, 1918–1923.
- [27] ANSYS Fluent Theory Guide, ANSYS, Inc., Release 15.0, 2013, <http://users.abo.fi/rzevenho/ansys%20fluent%2018%20tutorial%20guide.pdf>
- [28] Xie, Y.-N.; Ma, Y.-H.: Design of a multi-disciplinary and feature-based collaborative environment for chemical process projects, *Expert Systems with Applications*, 42(8), 2015, 4149–4166. <https://doi.org/10.1016/j.eswa.2015.01.009>
- [29] Yin, C.-G.; Ma, Y.-S.: Parametric feature constraint modeling and mapping in product development, *Advanced Engineering Informatics*, 26(3), 2012, 539–552. <https://doi.org/10.1016/j.aei.2012.02.010>