Coupled hybrid modelling in fire safety engineering; a literature review

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Abstract:

Systems in the built environment are getting bigger and more complex. Fire safety engineers are required to analyse these structures to ensure acceptable levels of safety. Computational limitations mean that the calculation domain must be curtailed. This ignores the two-way coupling between the total system and a fire. Coupled hybrid modelling (coupling of fire dynamics sub-models with a range of computational costs) expands the domain and analyses this two-way coupling within a reasonable timeframe. This article presents a literature review of this modelling paradigm and has application for those investigating and expanding the method.

Over the last quarter of a century, researchers have investigated coupled hybrid modelling but work has been in disconnected streams. There has been no review of coupled hybrid modelling for fire safety engineering. It is unclear where the knowledge gaps are and where future work should be focused.

This review demonstrates that the method is numerically feasible and can reduce wall clock time for total system analysis. This review reveals that there is limited validation and a host of unresolved questions (including sub-model choice, interface modelling, domain decomposition and coupling method). This review draws attention to the lack of collaboration which has led to obsolete models and parallel working.

This article shows that coupled hybrid modelling has potential but effort is being squandered. This review is a stepping-stone towards a standardised coupled hybrid framework. This review highlights where future collaborative research should be directed.

Keywords:

Coupled modelling; hybrid modelling; multiscale modelling; CFD; field modelling; zone modelling; network modelling; fire safety engineering

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1. Introduction

1.1. Problem

The construction industry is driven by time constraints [1] and these constraints can lead to compromises in engineered safety [2]. As with other fields, this is true for fire safety engineers, designers and modellers. To deliver output within reasonable and expected timeframes, modellers curtail the domain to keep simulation runtimes low [3,4]; as shown in Figure 1. Modellers explicitly consider a small part of a total system (e.g. a single room in a building or a short section of a tunnel) and expand conclusions to the entire system [5].

Over half of fire fatalities in the built environment in the US, UK and Australia occur outside of the room of fire origin [6–8]. Over 65% of UK fire fatalities are due to smoke inhalation [9]. The entire building system and its ventilation have significant influence on how fire behaves and how smoke is generated and spreads throughout the system [10]. The current typical fire safety engineering modelling paradigm ignores this two-way interaction of the total system and the fire. The acuteness of this risk is increasing as buildings are getting taller [11] and more complex [12], tunnels are getting longer [13], and the whole built environment is becoming more reliant upon performance based design [14].

One of the solutions to address this issue is “coupled hybrid” modelling – coupling multiple sub-models, with the same function but with differing complexities and computational costs, into a single simulation tool. This coupled hybrid method enables modellers to expand the calculation domain and explicitly examine more, or all, of a total system [15,16].

1.1.1. What’s in a name?

Coupled fluid modelling has been investigated in a wide range of fields of study (haemodynamics [17], indoor air quality [18], building ventilation [19], including fire [20], tunnel ventilation [21], including fire [22], wildland fire [23] and climatology [24]). Each field has slightly differing terminology for this method; including coupled, hybrid, integrated, multiscale, two-scale, multi-dimensional, 3D-1D, field-zone, field-network and others. In this review, we adopt the catch all term “coupled hybrid” to describe the coupling of two or more sub-models (which have the same overarching function) into a single hybrid model. It is acknowledged that some coupled hybrid models may also be multiscale (work at multiple scales of time and space), 3D-1D (couple 3D and 1D fluid solvers), field-zone (couple a field model and a zone model), etc.

1.1.2. Modelling methods for fire and smoke

Here we present a short description of the model types discussed in this review. The definitions are not designed to be comprehensive explanations but instead to give a broad overview and to point those interested to further reading. The models are presented in order of increasing complexity and computational cost.

1D network models represent a system as a one-dimensional network of nodes (compartments or junctions) and node connections (ducts, tunnels, corridors or leakage paths). Nodes contain a single set of variables such as temperature, density, mass and are treated as homogeneous. Node connections represent 1D transfer conduits between nodes. Network models contain relatively simple forms of conservation equations such as the use of Bernoulli's equation for the conservation of momentum and hence enable a large domain to be analysed with low computational cost [25]. Examples of network models include the Subway Environmental Simulator (SES) [26] and Fire and Smoke Simulator (FSSIM) [25].

Zone models represent a compartment as multiple uniform zones (typically two zones: a hot upper layer and a cooler lower layer) with the inclusion of vents to represent doors and windows [27]. Zone models solve conservation equations between the uniform zones and typically include empirical relationships for phenomena such as fires, plume flow and corridor jets. Zone models are limited by the geometry they can represent (simple, cuboidal compartments) but are solved relatively quickly. Examples of zone models include CFAST [28] and BRANZFIRE [29].

Field models, also called computational fluid dynamics (CFD) models, divide a domain into finite elements or volumes for which conservation equations are solved. Each finite element holds a set of conserved variables. Field models can be used to examine complex geometry but require large storage space, high computation requirements and have a high computational cost. Due to typical meshing strategies, field models are not well suited to studying leakage through small gaps in a relatively large enclosure [30]. Examples of field models include FDS [31], SMARTFIRE [32] and FireFOAM [33].The term "coupled modelling" is sometimes also used in fire science to describe the coupling of field models and solid-phase heat transfer and structural response models [34,35]. These are not considered to be "hybrid" models (the sub-models do not perform essentially the same function) and are outside of the scope of this review.

2. Coupled hybrid modelling in other fields

The haemodynamics industry have employed coupled 3D-1D hybrid fluid models to simulate multiscale blood flow through vessels [17,36–41]. Coupled hybrid modelling in haemodynamics also incorporates unsteady geometric deformation of the vessel; typically via the use of FEM [42].

The automotive industry use coupled 3D-1D hybrid fluid and combustion models to simulate internal combustion engines [43–46]. Coupled hybrid methods enable the entire system, including combustion chamber, fuel injection, exhaust, intake and filters to be efficiently modelled. The method is used especially during engine development stage. 1D models typically used to simulate whole engine behaviour are phenomenological and require fitting to experimental data. To address the lack of validation data, 3D fluid models are used to capture complex combustion processes and pollutant generation [47].

Tunnel ventilation researchers and practitioners have developed and used coupled 3D-1D hybrid models for the "multi-dimension" design and assessment of ventilation systems and passenger comfort and safety [21,48–50]. In this industry the use of 1D network models to design ventilation systems is typical [26,51]. However, calculation of 1D junction loss factors is slow and labour intensive [52] and the required oversimplification of complex geometries at stations could introduce passenger comfort and safety risks [53].

The field of building simulation (the study of ventilation and air quality in buildings) use coupled hybrid modelling – these instances involve the coupling of a "multizone model" (a 1D network model) and a field model [19,54–60]. In building simulation, the field sub-model is typically used to simulate external wind conditions around the building and not features inside the building.

Wildland fire researchers use coupled hybrid methods, typically called atmosphere-fire coupling, to examine the interaction of wildfire and atmospheric systems [23,61–63]. Studies couple a field model (used to simulate mass and enthalpy flow in the atmosphere above a wildfire) and an empirical 2D fire spread model. The fire spread model provides a source of enthalpy to the atmosphere field model which then models large scale atmospheric flow and turbulence with a grid cell size of typically 20 – 100m.

3. Coupled hybrid modelling in fire safety engineering

In fire safety engineering, coupled hybrid modelling can be broken into three categories based on the selection of sub-models. The categories are coupled field-zone, field-network and zone-network hybrid models. The following sub-sections provide a literature review for each category in turn.

3.1. Coupled field-zone hybrid models

The earliest of the coupled hybrid model categories to emerge. These models are used to examine building and ship fires. These coupled hybrid models simulate the fire, the enclosure of fire origin and proximal enclosures in the field sub-domain and simulate medium to far field spaces in the zone sub-model. Refer to Figure 4.

Xu et al. [64] developed a coupled field-zone hybrid model and documented the results of a numerical demonstration case on a single storey, multi-room building. The field sub-model was 2D and was coupled to a bespoke zone sub-model. No validation of the coupled hybrid model was presented. Wang et al. [65] later extended the field sub-model to enable the consideration of 3D cases – the article is not scientifically thorough and presents a short summary of the extended model with no verification or validation.

Fan et al. [66], from State Key Laboratory of Fire Science of China, presented a field-zone hybrid method, coupling proprietary unnamed sub-models to create a new model called F-Z model. The field model used k-ε turbulence modelling. In the field sub-domain, the hybrid interface is a zero gradient Neumann boundary condition for all variables except the perpendicular velocity component which is output based upon mass conservation. In the zone sub-domain, the hybrid interface is a mass and enthalpy flux boundary condition – computed using relevant summations of variables (velocity, temperature, specific heat, species concentration and density) taken from the adjacent field sub-model grid cells. Heat losses to the bounding construction are ignored.

The authors validated the F-Z Model against medium-scale fire test data of a two-room arrangement with generally good agreement. The hybrid model over-predicts the peak gas temperatures in both the fire room and the connected room by approximately 3 – 10°C. The author states that this may be due to the omission of heat loss to the bounding walls. The validation case heat source was an electric heater; this limits the conclusions which can be drawn as phenomena such as changes to density and pressure due to mass flux from a fire, soot disposition and spatial variability of burning, due to low equivalence ratio, are neglected.

Fan & Wang [67] further developed the F-Z Model, describing an enhanced coupled field-zone-network hybrid model called FZN Ver. 3. Fan et al. [66] and Fan & Wang [67] contain disagreement in the model descriptions, with the latter publication describing the original F-Z Model as including a network sub-model. We presume that an unpublished version 2 of the FZN model introduced a network sub-model. The authors replaced the network sub-model with a single control volume zone sub-model and altered the zone sub-model pressure modification method. The former change is self-explanatory and the authors state that this optimises the code. There is no discussion of the effect of removing node connections, and hence axial velocity, from the network sub-model. The second change is that the zone sub-model of FZN Ver. 3 computes pressure modifications using energy and volume conservation – in contrast to the original model which used mass conservation. The authors state that this method converges faster and more reliably. The article describes the original method as unstable as compartment mass is an implicit parameter, whereas volume is constant and therefore less likely to lead to divergence. This is in contrast to CFAST 6's solution, which is based upon conservation of mass and energy [68]. The article presents no validation of the updated FZN Ver. 3.

Similarly to the 1992 F-Z model, the fire is modelled as a source of mass flow at a certain temperature. There is no discussion of heat loss and we assume this to be absent in the FZN Ver. 3 model.

Yao et al. [69] continues the coupled hybrid modelling work carried out by Fan and colleagues [66,67]. The FZN model comprises the coupling of the FAC3 (Fire And Combustion in three dimensions) field model with the two zone and the one zone model from the previous FZN Ver. 3 model. FAC3 uses k-ε turbulence modelling and the two zone model uses the multi-cell method presented by Chow [70]. The field sub-domain is extended in to the two zone sub-model domain (an overlapping domain decomposition, refer to Figure 5). The authors state that it would be difficult to model the field-zone interface boundary condition otherwise – this is in contradiction to later work by Burton [20], see below. A hybrid interface vent in the zone sub-domain is covered by the field sub-domain; the vent flows can be obtained directly from the field sub-model velocity data (in contrast to mass conservation adopted by Fan et al. [66]). For these hybrid interface vents, entrainment mixing is computed using an empirical relationship. In the one zone sub-domain, the two zone sub-model provides a velocity boundary condition computed using the pressure difference across the vent; entrainment mixing from the lower layer is ignored.

Yao et al. validated the FZN model using a half-scale experimental room and corridor arrangement with a 9.7 kW fire source in the room. No data are compared for the field-modelled fire room. The authors compare temperatures in the upper layer in the corridor for the test and the FZN model (i.e. two zone sub-domain). The FZN model predicts the general trend but over-predicts temperatures by ~10°C. The authors do not discuss how they define a layer height from the test results. The authors present a FZN model demonstration case of a five-storey building. As in the precursory FZN Ver. 3 model, heat losses to the bounding construction are ignored and the fire is modelled simply as a source of heated mass.

Hua et al. [71] present the development and testing of a coupled field-zone hybrid model called Hybrid Field and Zone Model (HFAZM). HFAZM couples a bespoke k-ε turbulence based field model and a bespoke zone model, which uses a mass and energy conservation pressure correction algorithm. This method is similar to CFAST [28] but is in contrast to Fan & Wang [67], who used energy and volume conservation. HFAZM models the fire as a source of heat and ignores heat loss to the boundary. In the field sub-domain, the hybrid interface is a pressure boundary condition, using zero gradient variables from the zone sub-model plus a hydrostatic distribution. In the zone sub-domain, the hybrid interface is a mass and enthalpy flux source, which is computed using adjacent field sub-domain density, velocity, specific heat and temperature data.

The authors compare HFAZM to the output of alternative numerical methods for a room and corridor arrangement, with the multicell method being used in the zone sub-model simulated corridor. Comparison is against a full zone model (CFAST) and a full field model (Fluent). There is good agreement between HFAZM and the full field model for steady state smoke layer height in the corridor, with maximum deviations at the end of the modelling period of ~40mm. Transient conditions in far field of the modelling domain are predicted less consistently with maximum deviations of ~300mm. The authors attribute this to lateral spread of smoke in the zone sub-model being ignored; though the multicell method is proposed specifically to address this limitation. HFAZM predicts corridor smoke layer heights closer to the field model results than the zone model results. There is no comparison of temperature. For this case, HFAZM reduced runtime by 83% when compared to full field calculations for a 70% reduction in the field domain (over unity). The case featured a small fire size (<100 kW) and a short runtime of 200 seconds. The article presents a demonstration case for a room/corridor/shaft/corridor arrangement over two levels; but does not compare to alternative simulation methods. The authors present no validation against experimental results.

Hua et al uses “critical temperature” to reduce the approximately continuous variability of the field data into the two-zone assumption required for input into the zone sub-model. This method incorporates the prescription of a temperature, above which all mass and energy flows into the upper zone and below which all mass and energy flows into the lower zone. This is a simplistic methodology and is heavily sensitive to the prescribed critical temperature. This method also introduces the possibility of the creation of energy at the hybrid interfaces.

Jie et al. [72], from State Key Laboratory of Fire Sciences of China, present a coupled field-zone hybrid model, called LFZ, based upon a large eddy simulation (LES) field solver (specifically Fire Dynamics Simulator (FDS)). The article does not state the version of FDS or the zone model used. It is reasonable to assume that Jie’s work is the continuation of that of others at the State Key Laboratory of Fire Sciences of China [66,67,69]. The proprietary FAC3 field code used previously appears to have been dropped in favour of the open source FDS code. The authors present the basic formation of the constituent solvers and state that the field sub-domain is extended over the zone sub-model vent consistent with Yao et al. [69]. Boundary conditions for the hybrid interface in the zone domain can be “obtained directly from the field modelling simulation results”. The article does not discuss hybrid interfaces in the field sub-domain.

The authors present the results of a full-scale fire test of a room and corridor arrangement and provide numerical output from the two zone models CFAST and BR12, full field results from FDS and results from the LFZ hybrid model. The peak fire size is not stated. All the numerical methods over-predict the maximum upper layer temperature by ~10 – 40°C with BR12 being the worst performing and CFAST, FDS and LFZ being very similar. Except for LFZ, all numerical methods predict the reduction in temperature following the removal of the fire source. LFZ under-predicts the enclosure cooling and over-predicts final temperature at 360 seconds by ~20°C. We assumed this to be primarily because LFZ does not model heat loss at bounding construction. FDS predicts the commencement of lowering of the layer height more accurately than all other models, which under-predict by ~90 seconds. Both FDS and LFZ predict well the reduction of layer height to its minimum and the value of this minimum, with final layer height being within ~100 mm.

Ren et al. [73] developed a training software targeted at firefighting in ships. The software incorporates a virtual reality (VR) interface, 3D visual representation of the sea, ship, flames and smoke and a coupled field-zone-network hybrid model which is stated to include fire spread modelling. The article is short and presents very little information on the coupled hybrid model; it is unclear how it interfaces with the 3D visual simulation used for the VR training. The authors state that the field sub-model uses LES turbulence modelling and incorporates manual and automatic water suppression modelling. The article neither presents the theoretical or computational basis nor verification or validation of the coupled hybrid model. The authors state that “the network model ignores fume flow and air flow”; we assume this means the network model contains no mass and ignores transient species transport. The article states that the enclosure of fire origin is modelled using the field sub-model, the immediately adjacent enclosures by the zone sub-model and the rest of the ship by the network sub-model. This appears to have been arrived at by anecdotal evaluation and not analysis of conditions in these spaces and the suitability of the sub-model. The article is too sparse to allow any useful comment on the use of a coupled hybrid model. The article was presented at a software engineering conference and does not prioritise fire safety science.#

Research carried out by Burton and colleagues [20,74,75] represents a comprehensive work package on coupled field-zone hybrid modelling and concentrates on ships and buildings. Burton developed and presented validation of a coupled field-zone hybrid model based upon the SMARTFIRE field solver package and two different zone models. Initially the coupled zone model was CFAST; however, due to pressure solution convergence issues, a novel zone model, called FSEG-ZONE, was embedded in SMARTFIRE. The problem with the use of CFAST was due to the differing scale time step used in the solving methods of the two sub-models; SMARTFIRE is an implicit solver whereas CFAST is explicit, with much smaller time steps. This led to SMARTFIRE outputting large fluxes to CFAST at large intervals and caused convergence problems. Burton therefore developed a bespoke "semi-implicit" zone sub-model, called FSEG-ZONE. The new zone sub-model is iteratively called until convergence for each field sub-model iteration; only then is the global time step advanced.

Interface boundaries in the field sub-model are pressure and temperature boundary conditions. The pressure comprises the zone room pressure, hydrostatic pressure distribution, dynamic pressure due to vent velocity and a "normalisation pressure" used to correct the treatments of pressure in the two sub-models. The computation adopts upstream values of temperature and density. In the zone sub-model domain, the interface boundaries are mass and enthalpy flux source or sink terms; output using upstream values of density, velocity, specific heat and temperature.

The authors chose to pass fluxes from the field sub-model to the zone sub-model as this empowers the less empirical and higher definition sub-field model to calculate interface fluxes. Conservation is ensured by passing fluxes in one direction only; this would be uncertain if fluxes were passed in both directions (due to the differing numerical method employed by the sub-models). This method agrees with work by Hua et al. [71] and Floyd [76] but in contrast to Fan et al. [66] who pass fluxes in both directions and Wang et al. [77] who pass pressures in both directions.

Burton draws two separate case types; which are defined as "open" and "closed" cases. Open cases are those in which the zone sub-domain has a connection directly to the open atmosphere – pressure in the zone sub-model can equalise rapidly with the outside. Closed cases are those in which pressure relief is only available via the field sub-domain. The latter case leads to pressure solution divergence when using the explicit zone model solver CFAST.

The author presents test cases comparing the FSEG-ZONE based hybrid model with a SMARTFIRE-only model with the zone sub-domain replaced with a simple vent to ambient. In all cases the hybrid model presented lower disagreement of results with full field simulations when compared to the simplified arrangement. Unsurprisingly, but importantly, the hybrid model performs better than simply ignoring the extended domain.

Burton documents six numerical comparison cases against full field results and one validation case against full field and experimental results. Cases are 3 to 11 room arrangements, fire sizes between 100 – 500 kW and include the heat source being removed during simulation. The CFAST hybrid model over-predicts upper layer temperature by 2 – 20%, under-predicts lower layer temperature by 10 – 20%, over and under-predicts layer height by -300mm to +200mm (with disagreement increasing into the zone domain) and predicts a leaning plume when the hybrid interface is near the fire (towards zone domain). The FSEG-ZONE based hybrid model without 1D conduction predicts well upper layer temperature and layer height (being bound by data reduction methods) and under-predicts lower layer temperature by 5 – 50%. When 1D conduction is implemented upper layer is under-predicted by 20% during cooling and lower layer is under-predicted by 30% during heating. The hybrid model agrees with experimental and full field results more than coarse grid field for layer temperatures and height. Burton postulates that the variance in hybrid predictions is due to the zone sub-model uniform layer variable assumption – which leads to gas with a higher temperature venting from the compartment and uniform conduction.

In their short article Jiao et al. [78] documents a new coupled field-zone-network hybrid model, aimed at assessment of fire in ships. The article is not from a peer reviewed resource, has limited content and is poorly translated, which reduces its usefulness – it is presented here for completeness. FDS, CFAST and a bespoke model are used for the field, zone and network sub-models respectively. There is no validation. The author omits discussion of the coupling methodology and use a simple method to define where the zone/network interface location: where hot layer height is 80% or greater the network solver is used. It is impossible to say whether this simplistic method yields acceptable results due to the lack of validation. The article discusses and defines a scale model of a ship fire test rig; however, no reference is made to tests being carried out and no results are presented.

3.2. Coupled field-network hybrid models

These coupled hybrid models have been mainly used for the examination of tunnel fires, where the total system may have a length of tens or hundreds of kilometres. This may be due to the prevalence of 1D network models in tunnel ventilation engineering. More recently this category has been applied to buildings and ships for the modelling of ventilation systems. Refer to Figure 6.

Li et al. [79] developed a coupled field-network hybrid model called Tunnel Network FIRE version 3 (TNFIRE3) which builds on the previous non-hybrid TNFIRE models. The coupled model hybrid is based upon an unnamed field sub-model, which uses k-ε turbulence modelling and the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) solver, and a bespoke network sub-model based on the Multidimensional Multiple-choice Knapsack Problem (MMKP) method. No information is given regarding hybrid interface boundary condition treatment. The network sub-model includes heat losses to boundaries. The sub-models are solved sequentially for each time step. The field sub-model output at time step t_n, solved using network sub-model data from time step t_{n-1}, provides boundary condition data to the network sub-model for the solution at time step t_n. The authors define a smoke concentration and a temperature field to model the fire. The authors present a test case of Tehran Subway Line 1 but no validation.

Jiang et al. [80] presented the preliminary description of a coupled field-network hybrid model, based on bespoke sub-models, which was aimed at examining fires in mine networks. The article is based on a brief discussion of the mathematical basis of the coupled hybrid model and omits any example test cases, verification or validation of the model. The nonlinear PDEs of the network sub-model are solved using the difference method of characteristic curves and the field sub-model, which uses k-ε turbulence modelling, is solved using SIMPLE.

The model features unsteady two-way fluid flow and asynchronously solves the constituent sub-models at each time step. The solution of the network sub-model at time step t_{n-1} provides the boundary conditions of the field sub-model at time step t_n, which is then solved to provide the boundary conditions for the network sub-model at time step t_n. In the field sub-model domain, at the hybrid interface, all variables (velocity, enthalpy, concentration, k and ε) are adopted based upon the network sub-model parameters. It is unclear how this could be the case as some parameters (e.g. y and z velocity component, k and ε) would not be tracked in the network sub-model. In the network sub-model domain, at the hybrid interface, the sums of each parameter from the field sub-model grid cells adjacent to the interface are used to define an equivalent ghost node which is inserted in to the network model. Jiang & Wang's hybrid model does not model any chemical reactions in the network sub-model, therefore any combusting of unburnt fuel or further oxidisation of CO is ignored. Heat loss to the bounding walls of the mine is ignored.

Deng et al. [81] present the further development of TNFIRE3, first published in Li et al. [79], a coupled field-network hybrid model for the assessment of tunnels. The coupled hybrid model is based upon the field code Phoenics, implementing k-ε turbulence modelling and a proprietary network model which is directly embedded in the field solver code. TNFIRE3 includes heat loss at the bounding walls of the domain. Deng states that, to "save cost and time", radiation modelling and combustion modelling have both been removed from the Phoenics solver. The article documents the broad mathematical basis of the coupled hybrid model and presents a demonstration case using TNFIRE3.

In the field sub-domain, the hybrid interface is a mass flux boundary condition at the field sub-domain inlet (with fluid properties being adopted from the network data) and a Neumann pressure boundary condition at the field domain outlet. In the network sub-model domain, the hybrid interface is a momentum source boundary condition at the inlet and a mass sink boundary conditions at the outlet. There is no discussion of the locating of the hybrid interface. This is a key item for coupled field-network models as the cross-section properties (flow field, temperature, pressure, etc.) are required to be approximately homogeneous for the network model assumptions to be valid. There is no validation of the coupled hybrid model.

Jung et al. [82] examined coupled field-network hybrid modelling for ventilation of tunnel rescue stations. They used the commercial codes STAR-CD [83] and SES [26] for the field and network sub-models respectively. The article presents a numerical demonstration case in which the rescue station is within the field sub-domain and the remainder of the tunnel network is in the network sub-domain. Indirect coupling is used with the steady state network sub-model being solved initially and the output being used as constant boundary conditions for the unsteady field model solution (Dirichlet velocity and mass flux boundary conditions).

Work carried out by Colella and colleagues [22,84–90] is a comprehensive examination of coupled field-network hybrid modelling in tunnels. Colella developed a coupled field-network hybrid model for the examination of tunnels based upon Fluent, using k-ε turbulence modelling, and a bespoke 1D network model. Fires are modelled as sources of heat and mass. The coupled hybrid model can use either indirect or direct coupling. Indirect coupling entails the initial running of the field sub-model to obtain characteristic pressure-velocity curves for ventilation devices and fires and the subsequent use of these curves as boundary conditions for the network sub-model. Direct coupling involves the feedback of data between the two sub-models until convergence within a simulation time step.

The sub-models provide spatially averaged integral pressure, temperature, velocity and mass flow rate to one another, depending on the direction of flow. The hybrid interface assumes that area, mean pressure, mean velocity and mean temperature are identical on either side of the hybrid interface. The sub-model domains are coupled by way of a Dirichlet-Neumann boundary condition (Dirichlet and Neumann in the network and field sub-model respectively) and are based on non-overlapping domain decomposition. This method is similar to Li et al. and Jiang et al. [79,80] but in contrast to Fan et al. [66]. Colella provides comprehensive grid size and interface location sensitivity analysis for all test cases and concludes that the interface should be located ~20 times the hydraulic diameter of the tunnel away from a fire or jet fan. The is no discussion of boundary layer effects and velocity profiles when moving from the sparse network sub-model to the field sub-model (i.e. at defective boundary conditions).

The coupled hybrid model is validated against full-scale steady state ambient (non-fire) conditions in a 1.2 km tunnel in Dartford, UK [86]. 80% of the tunnel's length is modelled in the network sub-model. The coupled hybrid results are in very good agreement with the experimental results having a maximum velocity deviation of 1 m/s and a general velocity deviation of 0 – 0.5 m/s. Output from the coupled hybrid model is compared to the output of a series of full field steady state fire condition cases for the same tunnel. Fire sizes of 10 – 100 MW are adopted in various ventilation conditions. The coupled hybrid results are in very good agreement with the full field results with maximum bulk velocity deviations of ~7% (favourably compared to ~70% deviations for full network model output). The use of the coupled hybrid model reduced runtimes from ~50 – 70 hours for full field simulations to ~2 – 4 hours; a 95% reduction in time for an 80% reduction in field domain. Colella presents an unsteady fire condition demonstration case for the same tunnel; this was not compared to full field results as the predicted runtime was three months.

Floyd [76] presents the verification and validation of the coupling of a network model to the field model FDS (version 5.5) produced by NIST. This article is the precursory work to the network model which is included in FDS version 5.5 onwards (“HVAC”). The network sub-model is based upon the MELCOR solver [91], which was used in the Fire and Smoke Simulator (FSSIM) network model [25] (a propriety code produced by JENSEN HUGHES). The network sub-model incorporates an explicit solver for conservation of mass and energy and an implicit solver for conservation of momentum (Bernoulli equation with wall and minor losses). The network sub-model is designed for HVAC ducts and nodes do not have volume. There is no unsteady transport of species or energy or heat loss in the network sub-model.

The sub-models are asynchronously coupled or loosely coupled. The network sub-model solution at time step t_n uses field sub-model data from time step t_{n-1} as boundary conditions, is solved for a “temporary steady state” (within that time step) and hence outputs boundary conditions for the field sub-model at time step t_n. This is similar to Li et al., Jiang et al. and Deng et al. [79–81] but in contrast to Burton and Colella [20,22]. In the network sub-model the hybrid interface is pressure, temperature and species boundary conditions. For inflows from the field sub-model, variables are the density weighted average temperature and species concentration and the area weighted total pressure (background pressure and dynamic pressure) from the field model. In the field sub-model domain, inflows from the network sub-model are represented by mass flux and temperature boundary conditions. The temperature is adopted directly from the network sub-model. The mass flux is calculated from the species concentration, velocity, duct area and gas density from the network model.

The article presents three numerical verification cases for flow losses, species concentration and mass conservation at non-uniform temperatures. The coupled hybrid model passes all verification tests. Floyd provides three validation cases, one against a canonical HVAC system solution from the ASHRAE Fundamentals handbook [92] and two against an enclosed space experimental test facility containing 23 compartments, four levels, 20 openings and three HVAC systems. There is very good agreement between the hybrid model and the ASHRAE solution, with a maximum error in pressure drops of ~2%. In the enclosed space experimental facility, two tests were carried out with a diesel pool fire. The first having no HVAC operating and the second with HVAC operating normally and then moving to smoke exhaust mode after 1 minute. There is very good agreement between visibility and velocity data for both tests, typically a ~10% maximum deviation. Floyd states that errors are expected to be primarily due to the lack of modelling of fan spin up/down times, differences in actual and reference table duct friction coefficients (one of the main drivers behind the work of Prince et al. [53] for tunnel ventilation modelling) and fan performances and heat release rate errors.

The network sub-model does not account for mass storage or transient transport time, chemical reactions or heat loss. Floyd states that as the pressure solutions of the sub-models are not tightly coupled an error may be introduced in the overall solution, however stating that this error will be small as in typical scenarios pressure changes slowly.

Vermesi [93] provides the opening for a stream of work from the Technical University of Denmark (DTU) and Imperial College London on the use of FDS+HVAC for tunnels. This workstream builds on the work of Colella but instead uses FDS 6 and the coupled network sub-model HVAC, in lieu of Fluent and a bespoke network sub-model. The fire is modelled as a source of heat and mass, in line with the methodology adopted by Colella. Vermesi carries out sensitivity studies of mesh sizing and location of field-network coupling location with respect to fire location across three numerical test cases.

Vermesi carries out numerical comparison cases against the full field and coupled hybrid model output data published in Colella [22]. There is a general agreement although a reliance on visual results make it hard to make absolute comment on the veracity of agreement for temperature and velocity fields. The modelling method does not account for heat loss at bounding construction or any environmental factors at the portals (they are zero-friction Neumann boundary condition vents).

Tao et al. [94] presents a coupled field-network hybrid model for the examination of urban traffic link tunnel (large tunnel network) fires. The field sub-model, which uses k-ε turbulence modelling, is not stated and the network sub-model is a bespoke solver. Analysis is steady state and the sub-models are iteratively run until coupled hybrid model convergence. The output of one sub-model is used as boundary conditions for the next step in the iteration of the other sub-model. The fire is modelled as a source of mass and heat and heat loss to the boundary is not considered. Tao et al presents a numerical demonstration. There is no verification or validation presented.

Ang et al. [95] continue work on FDS+HVAC for tunnels and presents validation of the coupled hybrid model for the steady state non-fire tunnel experiments given in Colella [22]. They carried out a sensitivity analysis to investigate the effect of the limitations of the rectilinear meshing strategy in FDS 6.1.1 in representing a curved tunnel section. A rectangular and a stepped tunnel cross section is examined and the mass flow is shown to be within ~2% of each other. FDS+HVAC gives very good agreement with steady state experimental measurements of velocity for a range of jet fan arrangements, with predictions being bound by experimental error estimates. The results were shown to be sensitive to the geometric jet fan modelling method and the skin friction of the tunnel. The 1D network sub-model used less than 1% of the total CPU time and the use of the coupled hybrid model reduced runtimes by ~50% for a ~50% reduction in field domain. Heat losses in the network sub-domain are not accounted for.

Vermesi et al. [96] further build on the FDS+HVAC for tunnels work and investigate the potential for combining coupled hybrid modelling with parallel processing. The article compares the steady state results from FDS+HVAC to that of the coupled hybrid model developed in Colella [22] for the 1.2 km long tunnel fire scenario documented in Colella et al. [87]. The temperature is in good agreement with differences of ~2%. The velocity, however, is not in good agreement, especially near the fire, though only visual output is shown of this metric. The authors state that this is due to the way the fan was modelled within the network sub-model and if a quadratic fan curve had been used, the throttling effect of the fire would have been captured (refer to Vaitkevicius et al. [97] for further discussion). The combined use of coupled hybrid modelling and parallel processing is shown to decrease runtime by ~99% for a ~66% reduction in field domain. Similarly to Ang et al. and Ang [95,98], heat losses in the network sub-domain are not modelled and the coupled hybrid model presents false/numerical oscillations of mass flow.

Given the continuous development and integration cycle used in the FDS project, there have been incremental improvements in the coupled hybrid model capability. The author of this review has expanded the coupled 1D network model HVAC in FDS 6.5.3 [31] to compute the unsteady transport of species and energy through the network sub-domain using an explicit Euler method. The FDS

Verification Guide [99] presents various numerical verification cases of the transient coupled hybrid model against canonical solutions and first principles, which are passed with very low or nil tolerances. The network sub-model does not account for heat losses, allow for nodes with a volume and the unsteady conservation equations are based on pure advection. The FDS Validation Guide [100] presents the validation of FDS+HVAC (non-transient network sub-model) using experimental data from the PRISME Project [101] and the Lawrence Livermore National Laboratory (LLNL) enclosure experiments [102]. Upper layer and surface temperatures are predicted well (maximum deviations of ~20°C and ~10°C respectively), gas species concentrations are predicted reasonably well (maximum O_2 volume fraction deviations of ~0.05), pressure is predicted very well (maximum deviations of ~10 Pa) and heat flux is predicted reasonably (maximum deviations of ~1 kW/m^2). Validation is not provided for the coupled hybrid model using the transient network sub-model.

3.3. Coupled zone-network hybrid models

The last of the three coupled hybrid model categories is the sparsest. Aimed primarily at building and ship ventilation, there is an emphasis on the development of the network sub-model. The fire is located within the zone sub-model and vertical shafts are simulated using the network sub-model. Coupling is invariably one-way.

Zhu [103], from Carleton University, presents the development and testing of a coupled zone-network hybrid model for buildings. The work centres primarily on the development of the network sub-model and there is little discussion of the zone sub-model or the coupling methodology. Zhu evaluates many nonlinear ordinary differential equation (ODE) solvers to justify the chosen solvers adopted in the network sub-model pressure equation. He concludes that the Newton-GMRES solver with the Krykov subspace method is the best suited solution method. The temperature equation is solved using the DLSODE solver. The pressure component of the network sub-model solves substantially quicker than the temperature component. Therefore, the pressure and temperature solver are uncoupled and are batch solved in series assuming the other parameter remains steady in the given time step. Zhu states that this avoids stiff ODEs in the pressure and temperature equations. This uncoupled method could reduce predictive validity, due to assumption of lack of feedback within a time step, however the author claims that errors are within acceptable limits due to the small time steps.

The author presents numerical comparisons of the constituent zone and network models with CFAST and CONTAM respectively for a small single-storey building, a multi-room single storey building and a ten-storey apartment block. The analysis demonstrates generally good agreement with the comparison methods. A demonstration case of the coupled hybrid model is presented for a ten-storey building. No validation is presented.

One-way coupling between the zone and network sub-models is completed manually by running the zone model, outputting vent mass flow rates and temperatures and inputting these data into the network model as mass sources. Zhu uses ceiling vents and does not discuss the method by which two zone data would be reduced in the case of a wall vent (e.g. door) to enable it to be passed to the network sub-model. The coupled hybrid model ignores heat loss to the boundaries and the fire is modelled as a source of mass at a temperature.

The ASHRAE Research Project RP-1328 [104,105] is a continuation of the work carried out at Carleton University by Zhu [103]. RP-1328 involved the development of a zone-network hybrid model based upon bespoke zone and network sub-models. Kashef et al. [104] contains the theoretical background and development of the two sub-models. As per Zhu [103], Kashef's coupled hybrid model incorporates only one-way coupling (mass fluxes from the zone model are passed to the network model). This is justified with the assumption that mass fluxes will always be from the zone sub-domain (room of fire origin) to the network sub-domain (far field). This makes it difficult to state that the model would be valid for large complex buildings where unsteady changes in ventilation could lead to reversing mass fluxes. In contrast to Floyd [76], the network sub-model tracks mass storage in the network sub-domain. At the hybrid interface, the network sub-model mass flux boundary condition simply adopts the temperature of the upper layer in the zone sub-model no matter the location of the hot layer. The coupling and solution methodology employed by Kashef is relatively simplistic and incorporates the steady state solution of the zone sub-model and the subsequent one-way coupling of these results to a separately-solved network model.

Hadjisophocleous et al. [105] present further numerical comparison cases and optimisation of the RP-1328 coupled zone-network model developed in Zhu [103] and Kashef et al. [104]. The article presents numerical comparison cases for the constituent sub-models; the zone model against CFAST and the network model against CONTAM. The article notes that the solving of the network sub-model takes longer than the solving of the zone sub-model component. Although the network sub-model is substantially less complex than the zone sub-model, there are many more instances of the former. Hadjisophocleous introduces an adaptive time step which, for an undefined test case, it is claimed to reduce the network sub-model run time by an order of magnitude whilst giving the same results.

Hadjisophocleous et al compare the results from the zone sub-model to that of CFAST for a two storey, four room test building using a 1MW fire. The zone models are in general agreement, however the coupled hybrid model's network sub-model predicts a ~40°C greater temperature in the room of fire origin at the end of the simulation (300 seconds). The second comparison case is that of the network sub-model to a CONTAM network model. Due to the limitations of the models, the fire is modelled as a mass flow source with a temperature of 77°C; this temperature is considered too low to represent a typical building fire. The general agreement between the models is good; however, there are some nodes for which the results are orders of magnitude apart. For both comparison cases, it is impossible to state which model is the most valid due to lack of experimental data and the author provides no evaluation of the differences. One-way manual coupling of the zone and network sub-models and lack of coupled hybrid model testing or validation presented in Zhu [103] continue.

Zhang et al. [30] documents a coupled zone-network hybrid model aimed at the examination of smoke spread in stair and elevator shafts and smoke control in tall buildings. The zone sub-model domain only comprises a portion of the fire floor and is manually one-way coupled to the network sub-model very simply. The hybrid interface is represented by a temperature boundary condition with the temperature computed by the spatial averaging of the upper and lower layer of the zone sub-model. This is simplistic and could lead to erroneously high or low boundary condition temperatures in the network sub-model. Convective and radiative heat losses are accounted for in the network sub-domain; as per TNFIRE3 [81] and Colella [22] and unlike the F-Z/FZN/LFZ model [79,80] and FDS+HVAC [31].

Validation is carried out against a medium scale experiment of a 1.5 m shaft and connected room which contained an ethanol fire. There is good agreement between the network sub-model and the experimental results with a maximum difference of ~20°C. The article presents a demonstration case for a 30-storey single shaft building and investigates the effect of different door opening/closing arrangements.

4. Summary of fundamental coupled hybrid components

The following section is a summary of the treatment of poignant pieces of the coupled hybrid modelling paradigm in fire safety engineering. It serves to highlight where the literature contains agreement and where does not.

4.1. Sub-models used and coupled hybrid model purpose

Different coupled hybrid model types are possible; based upon the constituent sub-models adopted. The choice for which sub-model type to adopt is based upon what element of the built environment is being examined and the type and extent of output required to perform the desired analysis.

Where tunnels are the subject of analysis, all authors have adopted a field-network modelling methodology [22,79,81,93,94]. Some authors have also taken advantage of primarily unidirectional flow in tunnels to model only one directional coupling between sub-models. The lack of adoption of a zone sub-model is because this model type, at least in its typical state, is not useful for a tunnel. A zone model does not typically account for lateral variation in parameters or lateral movement of mass; therefore, information related to smoke spread, back-layering and critical velocity in a longitudinally ventilated tunnel is not resolved. Authors have attempted to use zone models in a “multicell” arrangement for tunnels [106–108] although this is not discussed in here. Network models lend themselves to tunnels as they can output the variation of variables of interest, such as pressure, enthalpy, velocity or temperature, through the length of the network [26].

In buildings and ships the choice of constituent sub-model has been less unanimous with all three options being adopted. Early examples were based upon a field-zone methodology and this continues to the majority of contemporary models (F-Z/FZN/LFZ model [65,66], HFAZM [71] and SMARTFIRE/FSEG-ZONE [20]). Zone sub-models are more suitable for buildings and ships as the complete mixing assumption of network models is not realistic for a room enclosure near to a room of fire origin. Zone sub-models can be used to more realistically represent the behaviour of the proximal enclosures which are not the room of fire origin when compared to a network sub-model. A zone sub-model can output vertically variable enclosure conditions (within the limits of the two-zone assumption) and this can be used to test relevant acceptance criteria (e.g. clear height, temperature at head height [109]). A limitation of this method is the representation of enclosures suitability far away from the fire origin such that the two-layer assumption is not true and/or homogeneous conditions have been reached. The representation of a HVAC system cannot be validly modelled in a two-zone model due to strong and variable bulk flow characteristics in the duct parallel to the direction of the duct.

One logical conclusion of the above discussion of the limitations of using only a zone sub-model is to also include a network sub-model. This field-zone-network method has been adopted by a small number of authors (F-Z/FZN/LFZ model [67,69], Ren et al. and Jiao et al. [73,78]). The rationale of this method is the modelling of the very far field enclosures and air-handling systems, that is, parts of the domain where the homogeneous assumption is valid, in the network sub-model.

FDS+HVAC [31,76] adopts a field-network methodology. It should be noted that this coupled hybrid model was aimed specifically at air-handling infrastructure (hence it is named HVAC) and therefore the assumptions imbedded in the network model (homogeneous parameters across a cross section) are relatively valid. An interesting development of this method is the work from DTU and Imperial College London [93,95,96,98], who use this coupled hybrid model with full height vents to simulate a tunnel. Although the network sub-model was not initially intended for this purpose, documented results look promising.

The remaining published model, RP-1328 – developed at Carleton University, disavow use of a field sub-model and adopt a more simplistic coupled zone-network hybrid method. This coupled hybrid model type would not be able to capture the 3D flow field surrounding complex geometry. Combustion modelling is more simplistic and would not account for the propagation of unburnt fuel in underventilated fires. This model type is more susceptible to inaccuracies outside of the relevant validation range due to the empirical nature of the primary solver (the zone sub-model). Runtimes would be substantially quicker that a coupled hybrid model which contains a field sub-model.

To summarise, there is a unanimous choice for the examination of tunnels to use a coupled field-network hybrid method, however no such choice has been made for buildings and ships. Most authors adopt a coupled field-zone hybrid model for this application although coupled field-network hybrid models have been developed also. One body of work adopts a coupled zone-network hybrid method. It cannot be stated that one choice of sub-model(s) is any more correct than any other, instead it is important to define what the required output and end user expectations of the coupled hybrid model are and verify that these requirements are met by the adopted sub-model choices [110].

4.2. Coupled hybrid interface boundary conditions

A major element of any coupled hybrid model is the treatment of the boundary conditions in the sub-models which represent the hybrid interface. Valid and sensible boundary conditions ensure that the problem is mathematically well-posed [111] and that conservation is ensured. Boundary conditions are also affected by the choice of domain decomposition used (overlapping or non-overlapping). The following table summarises the choice of boundary condition in the reviewed literature.

4.3. Numerical coupling procedure

There are a wide range of coupling procedures. They are all based on assumptions, model requirements and application. This is a major issue for all coupled hybrid models. It affects code stability and convergence, and computational cost. Many authors omit any relevant discussion (Xu et al. [64], the F-Z/FZN/LFZ project [66,67,69,72], HFAZM [71] and Ren et al. [73]). In the table below we summarise the different numerical coupling methods.

4.4. Extent and results of validation and comparison studies

There is a vast range in the volume, quality and applicability of validation work which has been carried out on coupled hybrid models. Approximately 50% of the published works are related only to the mathematical development of the constituent sub-models, the coupling methods and/or presentation of numerical demonstration cases [67,78,79,81,94]. Although these works are useful in enlightening the reader and serve to demonstrate a coupled hybrid model can produce output which appear to produce realistic results, they are critically limited in their validity and safe usability.

There is a body of validation work of varying soundness. Authors have presented both numerical comparisons and experimental validation [20,22,66,69,72,74–76,84,86,88] and others only numerical comparisons are provided [71,103–105].

The advantage of numerical comparisons is that they are easier, cheaper and quicker to carry out when compared with experimental validation. This means that many comparison cases can be completed. Statements related to the output of a coupled hybrid model compared to an alternative numerical method (which is widely used and societally trusted) can be made. We can say that the output of a coupled hybrid model is similar to an established numerical model which is used within a certain set of limitations to model the real world. The disadvantage of carrying out only numerical comparisons is that no statement can, per se, be made on the ability of the coupled hybrid model to represent the real world [112]. Depending on the level of validation of the numerical model used to provide the comparison case and the extent of the test case we may only conclude that the tested coupled hybrid model provides similar output to an existing model. Care should be taken to not make statements such as “therefore the coupled hybrid model is at least as good as the comparison model”. Variation between the coupled hybrid model and the unimodal comparison model could indicate that the coupled hybrid model is either predicting real behaviour more, or less, accurately than the unimodal model. Without experimental data, it is typically impossible to conclude which statement is true.

When comparing with other numerical methods and validated with experimental data, there is a distinction to draw between (1) literature which contains numerical comparisons and experimental validation for different test cases and (2) those which, in a single case, involve numerical and experimental comparison. The former does not, ipso facto, increase the absolute real world validity of the numerical comparison cases. The latter provides richer validation and the opportunity to make statements regarding the representation of real behaviour. The advantage of comparison with both numerical and experimental data in a single test case is that if the separately validated unimodal model agrees with the limited experimental data then the richer unimodal model data can be used for further validation in the test case. For fire tests, one limitation is limited instrumentation. However McGrattan et al. [112] argue that “quantity [of experiments] makes up for lack of quality [of individual experiments]” and that many more data points can overcome the limitations of experiments of lower quality when used with a statistical validation analysis.

The problem with much of the experimental validation cases [66,69,72] is that the test case has a small domain. They comprise of two or three enclosures. They are not representative of the probable end use of a coupled hybrid model and the applicability of these cases as true validation is compromised. The simpler constituent sub-models, being zone or network models, lend themselves to enclosures remote from the fire origin. In a two or three room test case this is not the case and the validation may not be “fair” to the coupled hybrid model as it is being tested outside of its planned remit. The prototypical use of a coupled hybrid model is to explicitly model more, or all, of a total system. Poor performance in these low enclosure cases is not a failure of the coupled hybrid model for the intended use.

5. Conclusion and future work

Coupled hybrid modelling for fire safety engineering applications is numerically realisable. Verification shows technical soundness and demonstration cases present very promising computational cost reductions at or above field domain reduction ratio unity. Numerical comparison cases and limited experimental validation show generally good agreement. Coupled hybrid modelling has exciting promise for the future of fire safety engineering analysis of buildings, ships, mines and tunnels. The capability of coupled hybrid models to provide a computationally efficient method of high level risk analysis of elements of infrastructure (using the lower order sub-models), whilst offering the ability to scale up the fidelity of output in areas of highlighted risk within the same simulation framework (using the higher order sub-models), lends the method to risk analysis of existing and new infrastructure. The same model can be scaled over a range of levels of required output resolution to further investigate cases highlighted during a higher level initial risk analysis exercise.

Like any under-developed and disparately investigated avenue of research there are fractured opinions regarding the various sub-problems and little agreement as to the correct solution method [113]. Unresolved questions include: which sub-models to include, how to represent the hybrid interface boundary conditions, how to decompose the domain and the numerical solution method for coupling the sub-models.

Then there are the gaps. Experimental validation is critically lacking. Before a coupled hybrid model moves from being a research topic to being utilised by practitioners this deficiency needs to be addressed. Validation experiments need to be specifically designed (or chosen) to test a coupled hybrid model's capabilities and as it would be used in a real-world application. This dataset would enable the more thorough investigation of the most effective hybrid interface boundary conditions treatment and sub-model choices.

Lack of communication, structure and agreement leads to obsolete models and wasted work [114]. There are at least 168 different computer modelling programs for fire and smoke simulation; including 17 field models and 50 zone models [27]. Considering just coupled field-zone hybrid models, this gives 850 hypothetical coupled hybrid models; though a small fraction of these models are realistically available or actively maintained and used. Finite project-centric and non-collaborative model development has led to these demises. If there is no communication and collaboration, then these potential research silos could swallow even more resource, require parallel re-working and spit out soon-to-die coupled hybrid models. For the development of coupled hybrid models to be efficient and effective, there needs to be communication between research parties and community-led signposted collaboration. This impetus for collaboration is a motivation for the use of use open source software as part of coupled hybrid model development. The nature of open source software focuses collaboration, increases quality and gives users and developers freedom of customisability [115]. There is hope in this regard. Jie et al. [72] removed the closed source FAC3 from the State Key Laboratory of Fire Sciences of China coupled hybrid model and replaced it with the open source FDS. Work following on from Colella [22] replaced the proprietary Fluent with FDS [93,95,96,98]. In tunnel ventilation, Prince [21] used the open source FireFOAM field model and an embedded network sub-model, eschewing the proprietary SES. This trend should be continued, to decrease the number of dead coupled hybrid models and maximum knowledge exchange.

The positioning of the hybrid interface and the treatment of homogenous/heterogenous data at this location is an unresolved question. In tunnels, estimations have been made as to the distance away from a turbulence source where the homogeneous assumption of the network sub-model become valid (~20 times the hydraulic diameter away from a fire or jet fan [85]. There is limited agreement with this value [95]). This is important if using coupled hybrid models to study loss of stratification in tunnels. To capture the heterogeneity of the smoke density, the 3D field sub-model domain should be extended to at least the extent of the continuation of stratification. Else there is potential to introduce mixing sub-models in to the network sub-model to empirically study the loss of stratification within the 1D domain. In buildings, there has been no study of the sensitivity of results due to the proximity of the hybrid interface to the fire or ventilation elements. The acknowledgement that variables may well not be homogenous at hybrid interfaces and the treatment of communicating sparse data steer us to the consideration of defective boundary conditions [116]. Much work has been done on the treatment of defective boundary conditions when coupling 1D and 3D models in haemodynamics [111,117]. The conclusions made, and solutions formulated, by Formaggia and colleagues has informed the treatment of defective boundary conditions in tunnel ventilation via the use of the Lagrange multiplier method [118]. For coupled hybrid modelling in fire safety engineering, this remains an unanswered question.

There are limitations of the simulation methods. These may be (1) established weaknesses of the sub-models, (2) limitations due to the early stage of a sub-model or (3) novel problems due to the coupled hybrid model implementation. A full discussion of (1) is outside of the scope of this review but could include, for example, the uncertainties in prediction of heat release rate in a compartment fire using a field model [119], conductive heat loss and vent enthalpy flux errors due to the homogeneous variable assumption of a zone model [120] or inaccurate loss factors for duct fittings in network models [53]. (2) has a relationship with the previous discussion regarding collaboration. Researchers have generated multiple new models to use as a sub-model in a coupled hybrid model (e.g. the new zone sub-models of Hua et al. [71] and Burton [20] and the new 1D network sub-model of Colella [22]). Duplication of models has led to a patchwork of capability spread across a multitude of codes. The piecemeal capability profile should be collated into a consolidated number of sub-models. This applies mainly to the “add in” lower order sub-models (i.e. zone and network models). (3) is specific to the implementation of coupled hybrid models so is discussed in more detail in the following paragraph.

Zone models do not account for lateral spread of species or lateral velocities (except for at vents). This makes them unsuitable for the simulation of long corridors. If zone sub-models are to be used in a coupled field-zone hybrid model this needs to be addressed by implementing conservation of lateral momentum. Earlier versions of CFAST empirically accounted for lateral spread in corridors using a corridor flow delay sub-model. This was removed in version 7.0.1 and replaced with a Heskestad correlation model for ceiling jet velocity (no spread or delay). No coupled hybrid model accounts for heat transfer between sub-domains where these sub-domains coexist in space. For example, an HVAC duct (modelled in a network sub-model) passing through a room (modelled in a field sub-model), refer to Figure 10. This HVAC duct may be transporting hot fire products and would heat the room potentially leading to secondary ignition, this would be ignored by all current coupled hybrid models. Network sub-models should be expanded to account for obstructions in their domain (e.g. a carriage in a tunnel or objects in a corridor), more complex heat transfer (e.g. to simulate different wall boundary conditions of a corridor) and reacting flow.

In closing, coupled hybrid modelling offers a method for fire safety designers to efficiently model more of a domain of interest. Two-way coupling between a total system and a fire can be practicably investigated and the effect of this coupling understood within reasonable timeframes. Coupled hybrid modelling for fire safety engineering has application in any big, long or complex element of the built environment; for example, tunnels, supertall buildings and large complexes. The industry should consolidate the work already completed and fill the gaps in knowledge, understanding and application which have been highlighted in this review.

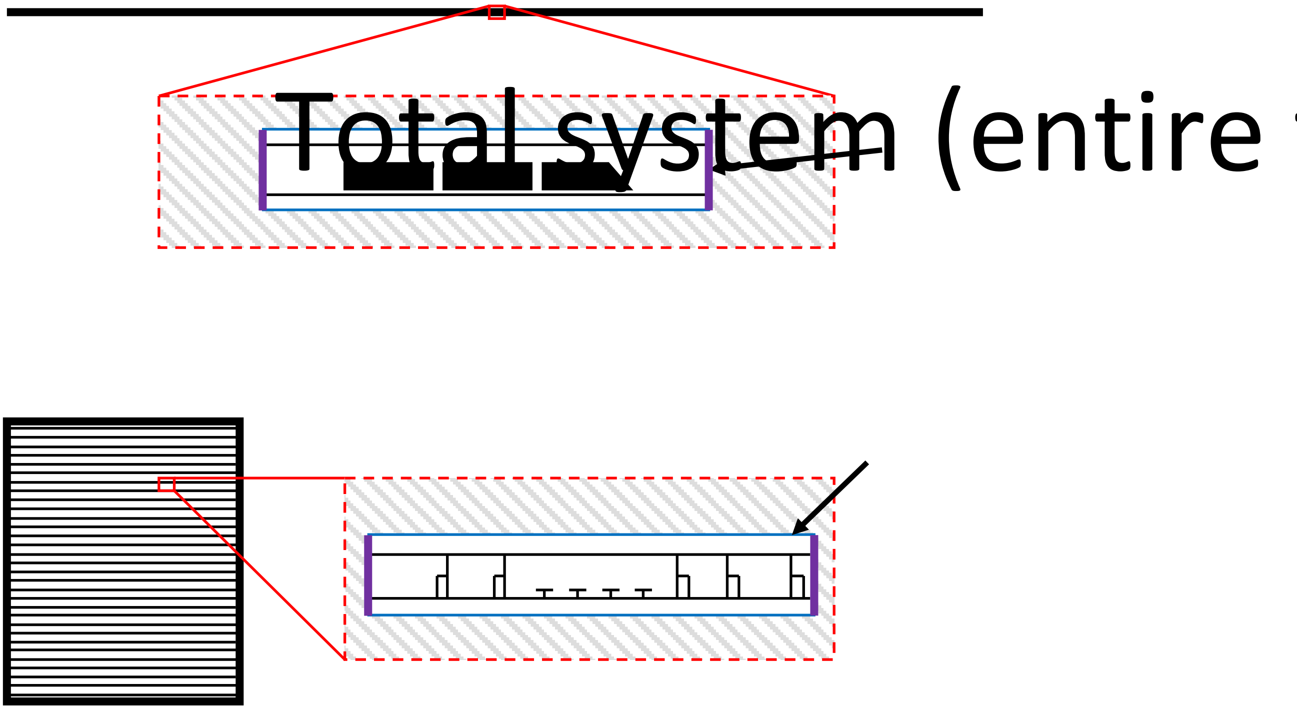

Figure 1: Typical fire safety engineering modelling paradigm

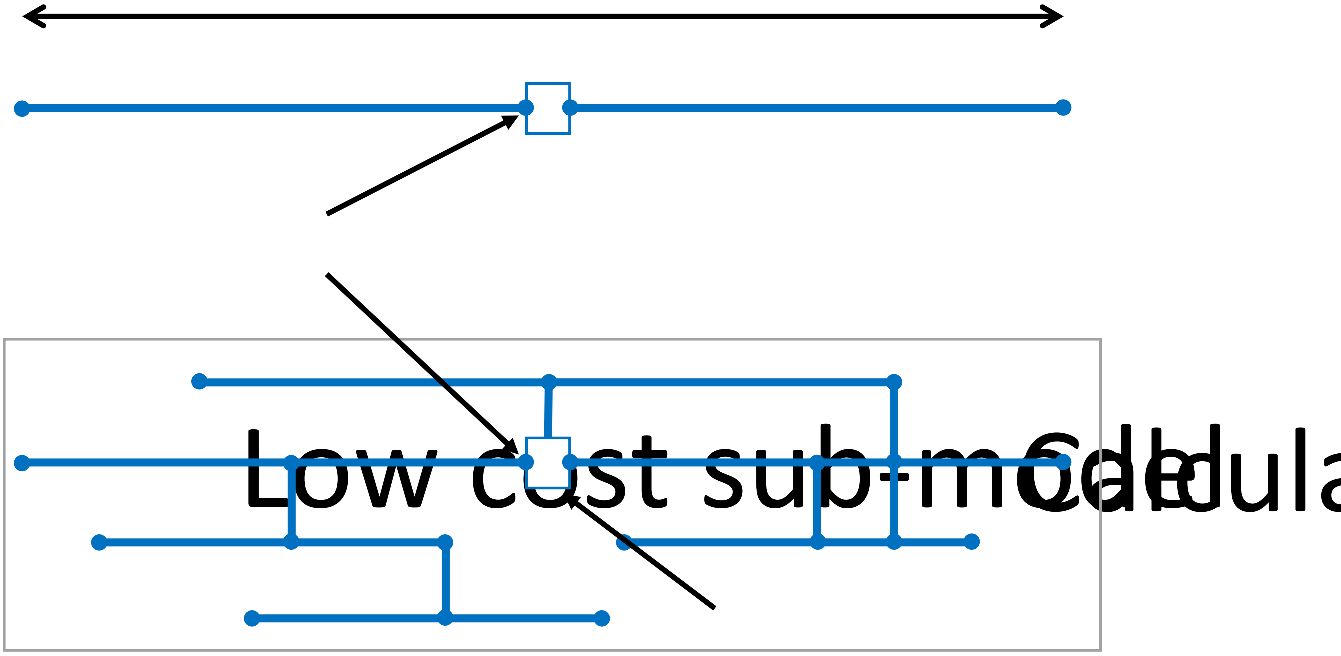

Figure 2: Schematic of coupled hybrid modelling for tunnels and buildings

Total system (entire

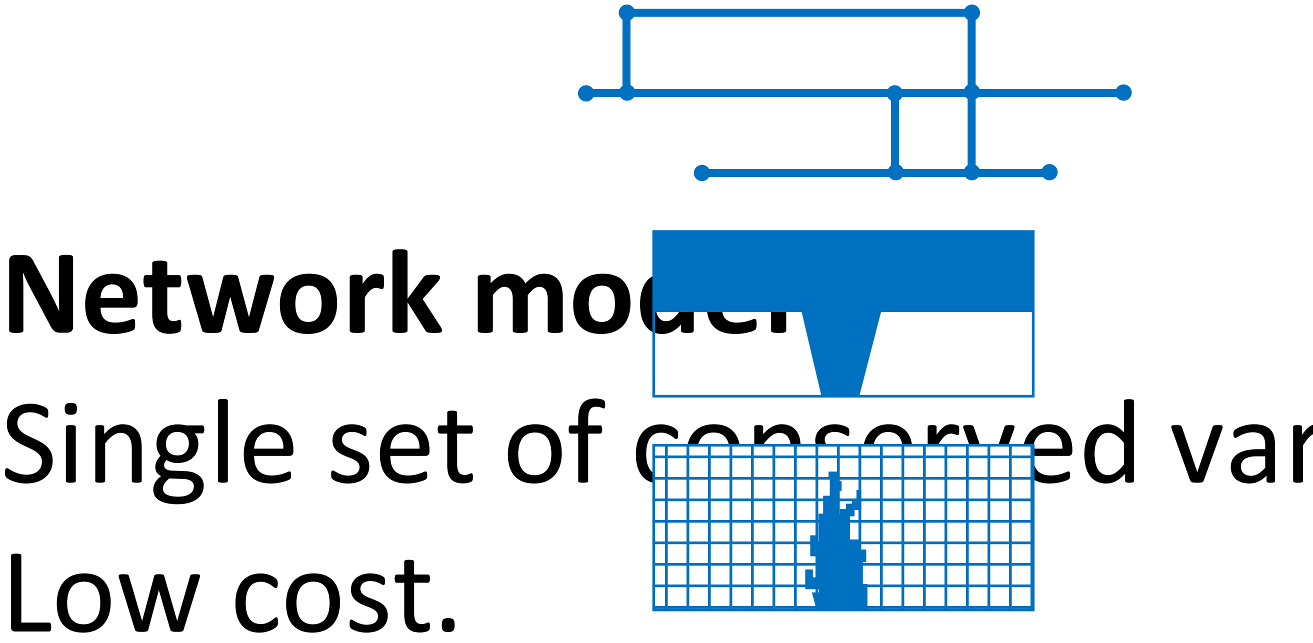

Figure 3: Hierarchy of typical fire safety engineering simulation methods

Figure 4: Coupled field-zone hybrid model schematic

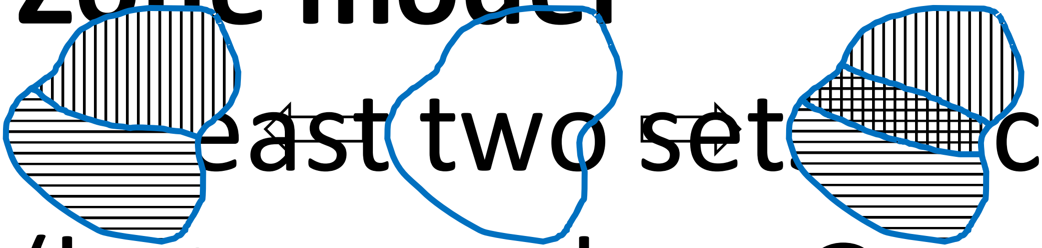

Figure 5: Domain decomposition methods

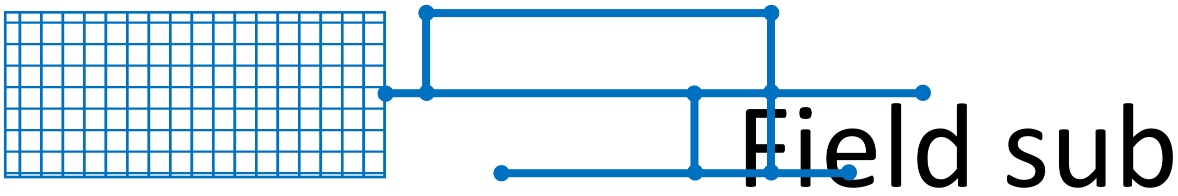

Figure 6: Coupled field-network hybrid model schematic

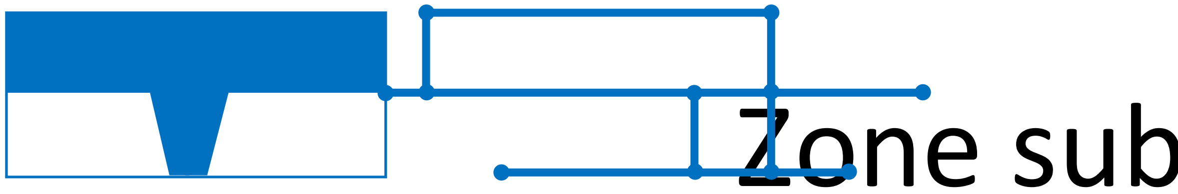

Figure 7: Coupled zone-network hybrid model schematic

Flow from field sub-model

To zone sub-model
- Fan et al. 1992; Hua et al. 2005; Burton 2011: Dirichlet mass and enthalpy flux.
- Yao et al. 1999; Jie et al. 2006: fluxes adopted directly from cells of overlapping sub-domain.

To network sub-model
- Jiang & Wang 1997: area sum of all variables inserted into ghost cell.
- Deng et al. 2007: Dirichlet momentum source.
- Colella 2010: Dirichlet velocity.
- McGrattan et al. 2017a: Dirichlet pressure, temperature and species concentration.

Flow from zone sub-model

To field sub-model
- Fan et al. 1992; Yao et al. 1999; Jie et al. 2006: zero gradient for all variables except velocity which is Dirichlet and computed based on mass conservation.
- Hua et al. 2005: zero gradient for all variables except pressure which is computed based on empirical pressure distributions.
- Burton 2011: Dirichlet pressure and temperature.

To network sub-model
- Yao et al. 1999: Dirichlet velocity computed from vent pressure drop.
- Zhu 2009: Dirichlet mass and temperature.
- Zhang et al. 2014: Dirichlet temperature.

Flow from network model

To field sub-model
- Jiang & Wang 1997: zero gradient for all variables.
- Deng et al. 2007: Dirichlet mass flux.
- Jung et al. 2010: Dirichlet velocity and mass flux.
- Colella 2010: Neumann pressure.
- McGrattan et al. 2017a: Dirichlet mass flux and temperature.

To zone sub-model
- Not applicable (relevant work used one-way coupling).

Figure 8: Summary of hybrid interface boundary condition type

Steady state one-way, "indirect coupling"	•Jung et al. 2010: Solve network sub-model to steady state convergence. Use output as boundary conditions for unsteady field sub-model solution. •Colella 2010 (one of two options): Solve field sub-model to steady state convergence. Output characteristic curves for ventilation elements. Use curves as boundary conditions for steady state network sub-model.
Steady state iterative	•Tao et al. 2014: Iteratively run network and field sub-models to steady state convergence, exchanging boundary condition data at the end of each iteration. Iterate until steady state global convergence.
Unsteady one-way	•Zhu 2009 and Zhang et al. 2014: Solve zone sub-model to t_{end} and store unsteady boundary conditions. Apply these boundary conditions to the network sub-model.
Unsteady asynchronous, "loose coupling"	•Li et al. 1995 (TNFIRE3), Jiang & Wang 1997, Deng et al. 2007 and McGrattan et al. 2017a (FDS+HVAC): Solve field sub-model at time step t_n using boundary conditions from network sub-model at time step t_{n-1}. Apply field sub-model boundary conditions for solution of network sub-model at time step t_n.
Unsteady direct, "fully coupled"	•Burton 2011 (SMARTFIRE/FSEG-ZONE): Iterate field sub-model, apply boundary conditions to zone sub-model and iterate until solution fully converges for that field sub-model iteration. Advance field sub-model iteration and re-solve. Iterate process until field sub-model convergence, then advance time step. •Colella 2010 (one of two options): Solve network sub-model to end of t_n, apply boundary conditions from network sub-model to solve field sub-model until end of time step t_n and apply boundary conditions to network sub-model. Iterate process until global convergence, then advance time step to t_{n+1}.

Figure 9: Summary of numerical coupling method and procedure

Figure 10: Schematic of domain overlap for a HVAC duct passing through an enclosure

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